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# CONTINUOUS AND ALTERNATING CURRENT MACHINERY

AN ELEMENTARY TEXT-BOOK FOR USE IN TECHNICAL SCHOOLS

BY

J. H. MORECROFT

*Assistant Professor of Electrical Engineering,*
*Columbia University*

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# PREFACE

At the present time the study of Electricity and Electrical Machinery occupies a very important place in the curricula of industrial schools, technical high schools and engineering schools. The application of electrical power is becoming so general that a knowledge of the simple principles and operating characteristics of the different types of electrical machinery is of great value to the man engaged in technical work of any kind.

This text was written especially for the use of students in technical high schools and similar institutions, but it is believed that it will be of value also for certain courses in engineering schools. Many of the students in engineering schools do not have the time for an exhaustive study of the subject of Electrical Machinery, but every engineering graduate should have some knowledge of the different kinds of generators and motors in every day use. To such non-electrical students the text should prove helpful.

In the preparation of this book the author has kept in mind the importance of simple, non-mathematical, explanations of the behavior of the various machines. A mathematical treatment of the subject has been introduced only when necessary; even then a rudimentary knowledge of mathematics only is required for a clear understanding of the subject matter.

I wish to express my appreciation of the courtesy the various electrical manufacturing companies have shown in furnishing me with the cuts used in the book.

S. H. M.

Columbia University,
January, 1914.

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# CONTINUOUS AND ALTERNATING CURRENT MACHINERY

## CHAPTER I

### ELEMENTARY PRINCIPLES AND LAWS OF CONTINUOUS CURRENTS

**1. The Electric Current.** Everyone is more or less familiar with some of the effects produced by an electric current. The exact nature of the current itself is not known but the magnetic action of a current, the heating action of a current flowing through a conductor, etc., have been accurately studied and the laws according to which the actions take place have been formulated and tested experimentally.

The four principal effects of an electric current are:

1. Production of a magnetic field.
2. Generation of heat.
3. Chemical action.
4. Physiological action.

*Magnetic Effect.* Whenever a current flows *a magnetic field is produced around the conductor through which the current is flowing;* a compass needle placed near the conductor carrying current will be deflected by such a field and the deflection will cease as soon as the current stops flowing.

*Heating Effect.* When a current is flowing through a conductor *heat is always generated in the conductor* and it may get very hot. The filament of an incandescent lamp and the electric welding machine, e.g., utilize this effect of the electric current. If the conductor is large in cross-section and the current not large, the heat generated may be very small, but no matter how large in cross-section the conductor may be or how small the current, some heat is always generated. The law expressing the rate at which the heat is developed will be given in a following paragraph.

*Chemical Effect.* In a city where electric trolley lines run through districts where iron water or gas mains are laid, it is often found that the iron pipes become disintegrated after a few years, due to the action of leakage currents from the trolley lines. The iron of which the pipes are constructed is made to combine with acids in the surrounding soil and is carried away; the action is called electrolysis. In a copper-plating establishment current is passed through a bath containing a solution of some copper salt and the copper is taken from the solution and deposited upon one of the metallic plates of the bath. These two actions illustrate *the chemical effect of a current.*

*Physiological Effect.* If a current of sufficient magnitude is sent through a living human being death is caused almost instantaneously. If the current is smaller the result may not be fatal, but severe muscular contractions occur, giving what is called an "electric shock." This is an example of *the physiological action of an electric current.*

**2. Electromotive Force.** In the previous paragraph the effects of an electric current were discussed but nothing was said as to how such a current might be produced.

*Generation of e.m.f. in a Primary Cell.* If two metal plates, one of zinc and the other of copper, are partly immersed in a solution of sulphuric acid and the outside ends of the two plates are joined together by a wire, an

electric current will flow through the wire. The current may be detected by any one of its actions as described in section 1. The question arises as to what action causes the current to flow through the wire. The wire by itself cannot produce a current, so it is evident that there must be some action in the vessel containing the two plates and sulphuric acid (called a **primary cell**) which action results in a current when the two plates are connected together outside the solution. Such a cell, which, by some internal action, *is able to produce and maintain an electric current* is said to generate an **electromotive force.**

It must be remembered that, if current is to be produced by the cell, the two terminals of the cell must be connected by some conducting body, i.e., some body through which an electric current passes freely. But such a cell generates an electromotive force (generally abbreviated to e.m.f.) whether its terminals are connected together or not. Some action takes place between the solution and the two metal plates of the cell and this action causes one plate to be at a higher electric pressure than the other. If two conducting bodies, between which there exists a difference of electric pressure, are connected together, current will flow from the point of higher pressure to that of lower pressure. The current is said to be caused by the e.m.f. of the cell but, as stated before, the cell generates an e.m.f. whether current flows or not.

*Generation of e.m.f. by Conductors Cutting a Magnetic Field.* A machine consisting chiefly of a set of conductors revolving in a magnetic field (an electric generator) has, when the conductors are thus made to move, some internal action which causes its two terminals to be so charged that there is between them a difference of electric pressure. If the terminals of the machine are connected by a wire, current will flow from one terminal to the other through the connecting wire, and this flow will continue as long as the connecting wire is left in place.

This machine which is able to continually maintain its terminals at a difference of electric pressure while current flows from one to the other, is said to generate an e.m.f. and is called an **electric generator.** Again, it is to be noticed that the machine generates an e.m.f. whether the connecting wire is used or not, i.e., whether current is flowing or not. The machine generates an e.m.f. *if it is capable of* sustaining a current between its terminals when they are connected by some conductor.

*E.M.F. Generated by a Thermo-couple.* If two strips of dissimilar metals are joined together and this junction is heated (the free ends of the strips being kept cool) the combination generates an e.m.f. This may be ascertained by connecting together the cool ends of the strips by a wire and testing for the presence of a current in the wire. Such a combination is called a **thermo-couple.**

X *Nature of e.m.f.* We may say in general that any device which is capable of sustaining an electric current through a closed circuit (of which circuit the device itself is a part) generates an electromotive force. With our present limited knowledge of electricity it is useless to try to give an exact definition of electromotive force because we know nothing about the nature of the force. In the same way we cannot describe in simple terms the force of gravitation. We only know that there is such a force as gravitational force and that, as a result of the action of this force, any two bodies in the universe are mutually attracted toward one another and if free from the action of other forces will move toward one another. Just as gravitational force tends to produce motion in material bodies, so electromotive force tends to produce motion of minute electrical charges existing in all conducting bodies; these electrical charges in motion constitute an electrical current.

**3. Conductors—Insulators—Resistance.** We have in the previous paragraphs referred to bodies which freely

permit the passage of an electric current as conductors. If the two terminals of an electric generator, or those of a primary cell, are connected by a piece of dry string, or a stick of dry wood, it will be found that no current passes through the connecting piece of string or wood; such bodies as these are called **insulators.** On the other hand, if the two terminals are connected by any metallic body, or by a piece of carbon, current will flow from the terminal of higher electric pressure to the one of lower electric pressure and such bodies are called **conductors.**

*Resistance.* Now if we make up a set of connecting pieces of various materials with which to join the terminals of the generator and have some means of measuring the amount of current that flows between the generator terminals when the different connecting strips are used, it will be found that the current which flows will vary with the different connectors. Although the e.m.f. of the generator is the same when the various connectors are used a heavy current will flow through some of them, a smaller current through others, and an imperceptible current through others. From this experimentally observed fact we get the idea of **resistance;** *apparently some of these connecting strips offer more resistance to the passage of an electric current than others.*

*Conductors and Insulators.* The difference between a conductor and an insulator cannot be sharply defined, because no body is a perfect conductor (one having no resistance) and no body is a perfect insulator (one having infinite resistance). This point must be kept in mind; for emphasis we will illustrate it by an example. If we make up a set of strips of various substances, all of the strips being of equal cross-section and length, then use them to connect the terminals of a generator and measure the amount of current that flows through each we might get results as shown by the table, page 6.

| | | | |
|---|---|---|---|
| Strip made of | copper........ | 100 | units of current |
| " " | iron.......... | 16 | " " |
| " " | mercury....... | 1.6 | " " |
| " " | carbon........ | $\frac{1}{2500}$ | unit of current |
| " " | selenium....... | $\frac{1}{40,000,000,000}$ | " " |

All of these substances are called conductors. If now we used other strips made of mica, glass, gutta percha, etc., some current would flow but it would be so small that all ordinary measuring instruments would fail to detect it; these strips would be called insulators.

*Resistance Depends upon Temperature.* The resistance of a body varies greatly with its temperature. In all metallic bodies the resistance increases with the temperature but in a few substances, notably glass and carbon and solutions of acids and salts, the resistance decreases greatly with increase in temperature. At all ordinary temperatures glass is a very good insulator; when red hot it becomes a good conductor.

The variation of resistance with temperature in all pure metals is found to closely follow the law given by the equation,

$$R_t = R_0(1+.004t), \quad \ldots \ldots \quad (1)$$

where $R_0$ = resistance of the conductor at 0° Centigrade.
$R_t$ = resistance of the conductor at $t$° Centigrade.
$t$ = temperature of conductor, above 0° Centigrade.
.004 = the *temperature coefficient* of resistance.

*Resistance Depends upon Size and Shape of Conductor.* For a body made of any given material it is found that the resistance varies directly with its length and inversely with the area of its cross-section; thus a piece of iron one foot

long and one square inch in cross-section would have one-tenth as much resistance as a piece of the same cross-section and ten feet long; the resistance of a piece one foot long and one-thousandth of a square inch in cross-section would be one thousand times as great as that of the first piece.

*Formula for Resistance.* The variation of resistance of a body with its cross-section and length is expressed by the equation,

$$R=\rho\frac{l}{a}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where $l$ = length of the conductor.
$a$ = area of cross-section.
$\rho$ = a constant, depending upon the material and upon the units in which $l$ and $a$ are measured.
$R$ = resistance in ohms.

Generally electrical engineers measure $l$ in feet and $a$ in circular mils, a circular mil being the area of a circle one-thousandth of an inch in diameter.

Then $\rho$ is the *resistance in ohms per mil-foot* of the substance of which the conductor is made. The constant $\rho$ varies greatly with different metals, being lowest for silver and copper; for some special alloys $\rho$ may be very large. A few metals have the following values for $\rho$ at 0° C.

| | | |
|---|---|---|
| Copper | 9.6 | ohms |
| Aluminum | 17.5 | " |
| Iron | 58.3 | " |
| German silver | 125.7 | " |
| Special alloys | 450.0 | " |

*Wire table.* It is convenient to have the resistance of copper wires put in the form of a table. Such a table is given here, the number of the wire being that given by the Brown & Sharpe gauge.

DIMENSIONS AND RESISTANCES OF PURE COPPER WIRE

| Gauge. No. | Diameter (Inches.) | | | Area | Weight and Length, sp. gr. = 8.89. | | Ohms per 1000 Feet. | | | Feet per Ohm. | Ohms per Pound. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Bare. | Single Cotton Covered. | Double Cotton Covered. | Circular mils ($d_2$) 1 mil = .001 Inch. | Lbs. per 1000 Feet. | Feet per Lb. | At 20° C. | At 50° C. | At 80° C. | At 20° C. | At 20° C. |
| 0000 | .460 | .......... | .......... | 211600.00 | 640.5 | 1.561 | .04893 | .05467 | .06058 | 26440. | 0.00007639 |
| 000 | .410 | .......... | .......... | 167805.00 | 508.0 | 1.969 | .06170 | .06893 | .07640 | 16210. | 0.0001215 |
| 00 | .365 | .......... | .......... | 133079.40 | 402.8 | 2.482 | .07780 | .08692 | .09633 | 12850. | 0.0001931 |
| 0 | .325 | .......... | .......... | 105592.50 | 319.5 | 3.130 | .09811 | .1096 | .1215 | 10190. | 0.0003071 |
| 1 | .289 | .......... | .303 | 83694.20 | 253.3 | 3.947 | .1237 | .1382 | .1532 | 8083. | 0.0004883 |
| 2 | .258 | .......... | .272 | 66373.00 | 200.9 | 4.977 | .1560 | .1743 | .1932 | 6410. | 0.0007765 |
| 3 | .229 | .......... | .243 | 52634.00 | 159.3 | 6.276 | .1967 | .2198 | .2435 | 5084. | 0.001235 |
| 4 | .204 | .......... | .216 | 41742.00 | 126.4 | 7.914 | .2480 | .2771 | .3071 | 4031. | 0.001963 |
| 5 | .182 | .......... | .194 | 33102.00 | 100.2 | 9.980 | .3128 | .3495 | .3873 | 3197. | 0.003122 |
| 6 | .162 | .......... | .174 | 26250.50 | 79.46 | 12.58 | .3944 | .4406 | .4883 | 2535. | 0.004963 |
| 7 | .144 | .......... | .156 | 20816.00 | 63.02 | 15.87 | .4973 | .5556 | .6158 | 2011. | 0.007892 |
| 8 | .128 | .......... | .140 | 16509.00 | 49.98 | 20.01 | .6271 | .7007 | .7765 | 1595. | 0.01255 |
| 9 | .114 | .......... | .126 | 13504.00 | 39.63 | 25.23 | .7908 | .8835 | .9791 | 1265. | 0.01995 |
| 10 | .102 | .108 | .112 | 10381.00 | 31.43 | 31.82 | .9972 | 1.114 | 1.235 | 1003. | 0.03173 |
| 11 | .0907 | .097 | .101 | 8234.00 | 24.93 | 40.12 | 1.257 | 1.405 | 1.557 | 795.3 | 0.05045 |
| 12 | .0808 | .087 | .091 | 6529.90 | 19.77 | 50.59 | 1.586 | 1.771 | 1.963 | 630.7 | 0.08022 |
| 13 | .0720 | .078 | .082 | 5178.40 | 15.68 | 63.79 | 1.999 | 2.234 | 2.476 | 500.1 | 0.1276 |
| 14 | .0641 | .071 | .075 | 4106.80 | 12.43 | 80.44 | 2.521 | 2.817 | 3.122 | 396.6 | 0.2028 |
| 15 | .0571 | .063 | .067 | 3256.7 | 9.85 | 101.4 | 3.179 | 3.552 | 3.936 | 314.5 | 0.3225 |
| 16 | .0508 | .055 | .059 | 2582.9 | 7.81 | 127.9 | 4.009 | 4.479 | 4.964 | 249.4 | 0.5128 |
| 17 | .0453 | .049 | .053 | 2048.2 | 6.20 | 161.3 | 5.055 | 5.648 | 6.259 | 197.8 | 0.8153 |
| 18 | .0403 | .044 | .048 | 1624.3 | 4.91 | 203.4 | 6.374 | 7.122 | 7.892 | 156.9 | 1.296 |
| 19 | .0359 | .039 | .043 | 1252.4 | 3.89 | 256.5 | 8.038 | 8.980 | 9.952 | 124.4 | 2.061 |
| 20 | .0320 | .036 | .040 | 1021.5 | 3.09 | 323.4 | 10.14 | 11.32 | 12.55 | 98.66 | 3.278 |
| 21 | .0285 | .032 | .036 | 810.10 | 2.45 | 407.8 | 12.78 | 14.28 | 15.83 | 78.24 | 5.212 |
| 22 | .0253 | .029 | .033 | 642.70 | 1.94 | 514.2 | 16.12 | 18.01 | 19.96 | 62.05 | 8.287 |
| 23 | .0226 | .027 | .031 | 509.45 | 1.54 | 648.4 | 20.32 | 22.71 | 25.16 | 49.21 | 13.18 |
| 24 | .0201 | .024 | .028 | 404.01 | 1.22 | 817.6 | 25.63 | 28.63 | 31.73 | 39.02 | 20.95 |
| 25 | .0179 | .022 | .026 | 320.40 | .97 | 1031. | 32.31 | 36.10 | 40.01 | 30.95 | 33.32 |
| 26 | .0159 | .020 | .024 | 254.01 | .77 | 1300. | 40.75 | 45.52 | 50.45 | 24.54 | 52.97 |
| 27 | .0142 | .018 | .022 | 201.50 | .61 | 1639. | 51.38 | 57.40 | 63.62 | 19.46 | 84.23 |
| 28 | .0126 | .017 | .021 | 159.79 | .48 | 2067. | 64.79 | 72.39 | 80.22 | 15.43 | 133.9 |
| 29 | .0118 | .015 | .019 | 126.72 | .38 | 2607. | 81.70 | 91.28 | 101.2 | 12.24 | 213.0 |
| 30 | .0100 | .014 | .018 | 100.5 | .30 | 3287. | 103.0 | 115.1 | 127.6 | 9.707 | 338.6 |
| 31 | .00893 | .0125 | .......... | 79.71 | .24 | 4145. | 129.9 | 145.1 | 160.8 | 7.698 | 538.4 |
| 32 | .00795 | .0115 | .......... | 63.20 | .19 | 5227. | 163.8 | 183.0 | 202.8 | 6.105 | 856.2 |
| 33 | .00708 | .0105 | .......... | 50.13 | .15 | 6591. | 206.6 | 230.8 | 255.8 | 4.841 | 1361. |
| 34 | .00531 | .0098 | .......... | 39.74 | .12 | 8311. | 260.5 | 291.0 | 322.5 | 3.839 | 2165. |
| 35 | .00562 | .0086 | .......... | 31.52 | .10 | 10480. | 328.4 | 366.9 | 406.7 | 3.045 | 3441. |
| 36 | .00500 | .0080 | .011 | 25.00 | .08 | 13210. | 414.2 | 462.7 | 512.9 | 2.414 | 5478. |

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For many approximate solutions it is sufficient to remember the constants for No. 10 wire only, as 1 ohm per 1000 feet and a cross-section of 10,000 circular mils. Other wires may be determined by remembering that the size of the cross-section of a wire doubles for every three numbers on the gauge. For example, No. 7 has an area of 20,000 circular mils and a resistance of 0.5 ohm per 1000 ft.; No. 16 has 2500 circular mils cross-section and a resistance of 4 ohms per 1000 ft.

**4. Units.** In previous paragraphs we have discussed current, e.m.f., and resistance but have not given the units in which these various quantities are ordinarily measured. Various systems of units have been employed in the past, but we shall work with the so-called practical system. Most of the units in this system are named after famous scientists. The units which we shall use mostly in the succeeding chapters are those of current, e.m.f., resistance and quantity of electricity. In addition to these there are the units of work and power and the units of the magnetic field, etc., which will be taken up later.

*Unit of Current.* The unit of current is the **ampere.** It is defined as that current which when flowing through a standard voltameter (in which a silver plate is immersed in a solution of silver nitrate) will deposit silver at the rate of 1.118 milligrams per second.

*Unit of e.m.f.* The unit of electromotive force is the **volt.** It is defined by fixing the value of the e.m.f. of a standard Weston cadmium cell. By international agreement the value of the e.m.f. of such a cell has been taken as 1.0183 volts so that we may say the volt is $\frac{1.0000}{1.0183}$ of the e.m.f. of a standard Weston cell.

The units of current, e.m.f., and resistance are fixed in their relation to one another by a simple equation called **Ohm's law,** which we shall take up in the next paragraph. Having fixed two of the units, the volt and ampere, it is

really needless to define the unit of resistance except in terms of the ampere and volt. However, the definition is often given in terms of a column of mercury so we add it here.

*Unit of Resistance.* The unit of resistance is called the **ohm** and is defined as that amount of resistance offered by a column of pure mercury 106.3 cm. long, having a uniform cross-section and weighing 14.4521 gms. at 0° C.

*Unit of Quantity.* The unit of quantity is the ***coulomb.*** It is defined as that quantity of electricity which is conveyed past any point in a circuit in one second of time by a current of one ampere.

**5. Ohm's Law.** It was experimentally determined by the celebrated physicist, Ohm, that there existed a direct proportionality between the e.m.f. in a given circuit and the current which flowed through the circuit. For a given circuit, if the e.m.f. was increased to twice its value, the current also increased to twice its value. If the e.m.f. was reduced to one-tenth of its value the current was decreased in the same ratio. When a direct proportionality exists between two variables, it is always possible to express the relation in the form of an equation by the use of a proper constant.

If $I$ = current in the circuit,

$E$ = e.m.f. in the circuit;

then Ohm discovered that $I \propto E$ and so we may put $E = kI$, where $k$ is some constant which will generally be different for every circuit. Now this constant $k$ is really what we call the resistance of the circuit (designated by $R$) and so we have the well known Ohm's law,

$$E = IR, \quad \ldots\ldots\ldots \quad (3)$$

which may also be written

$$I = \frac{E}{R} \quad \text{or} \quad R = \frac{E}{I}. \quad \ldots\ldots \quad (4)$$

This $R$ is generally designated as the "ohmic" resistance of a circuit, to distinguish it from "effective" resistance, a term the significance of which will be taken up in the chapter on Alternating Currents.

**6. Joule's Law, Electrical Energy, and Electrical Power.** It has been stated before that whenever an electric current flows through a conductor heat is generated in that conductor. Now heat is a form of energy which can be easily measured; ordinarily the unit of heat used in electrical engineering is the **gram-calorie,** which is the amount of heat required to raise one gram of water one degree Centigrade. If we can therefore measure the amount of heat developed by an electric current flowing through a conducting wire for a certain length of time, we can obtain a relation between the electrical quantities, difference of electric pressure (or voltage) and current, and the rate at which energy is given off from the conductor in the form of heat.

*Joule's Experiments.* By a series of experiments in which the heat given off by resistance wires was made to heat water in a closed vessel, the English physicist, Joule, was able to find a definite relation between the electrical quantities and the heat liberated. This equation, known as **Joule's Law,** is

$$Q_h = 0.24EIt, \qquad (5)$$

in which $Q_h$ = the amount of heat liberated in gram-calories;
$E$ = difference in electrical pressure, in volts, between the extremities of the conductor from which the heat is being liberated;
$I$ = current, in amperes, through the conductor;
$t$ = time, in seconds;
$0.24$ = the conversion factor.

As the electrical units and the heat units had been independently fixed, it was not to be expected that an equation

in which heat units are used on one side and electrical units on the other, would be free from some such factor. If the electrical units or heat units had been differently defined, this factor, 0.24, would have been different, and might possibly have been made equal to one.

*Importance of Joule's Law.* This equation is one of the most important there is in electrical science. It leads to a clearer understanding of what we mean by electric pressure and enables us to express at once the energy and rate of energy, or power, in an electric circuit.

From this equation we get the idea that

$$EIt = \textit{a quantity of work.}$$

$It$ = a quantity of electricity, in coulombs, and $E$ is a measure of the difference in electric pressure, or level, against which the quantity of electricity, $It$, has been moved.

*Hydraulic Analogy.* If a certain quantity of water, $A$ pounds, is lifted through a height, $B$ feet, we know that the amount of work done in the operation is equal to $AB$ foot-pounds. The $E$ of our electrical problem corresponds exactly to the $B$ of the hydraulic problem. And just as we know that water tends to flow from a higher level to a lower, so the electric current always tends to establish itself from the point of higher electric pressure or level to that of the lower level.

*Work Significance of Electric Pressure.* If in the hydraulic analogy above the amount of water, $A$, were unity, the product $AB$ would have the value $1 \times B$ or $B$. We may say, therefore, that $B$, the difference in level, also measures *the work done in lifting one pound* through the distance $B$.

Similarly, if in an electric circuit the product $It$ is equal to one, we arrive at another conception for $E$, the difference in electric pressure between two points. It is the *quantity*

*of work* necessary to carry a unit quantity of electricity from the point of lower electrical pressure to the point of higher pressure.

*Unit of Work.* The unit of work in the electrical system is the **Joule** and is the amount of work done in one second when a current of one ampere flows under a pressure of one volt.

In the form of an equation,

$$J = EIt, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where $J$ = electrical work in joules.

*Power.* Now *the rate at which work is being done* is evidently equal to $J/t$, but $J/t = EI$, so that the product $EI$ is a measure of the rate of energy, or power, of the electric circuit. The unit of power is the **watt,** and is the power represented by a current of one ampere flowing under a pressure of one volt. A more common unit in which electrical power is measured is the **kilo-watt,** which is equal to one thousand watts.

We have therefore the relation that watts $= EI$. But when $E = IR$ we also have Watts $= (IR) \times I = I^2R$, which is the equation ordinarily used in calculating the power used in a circuit in the form of heat.

**7. Potential and Difference of Potential.** Much confusion between the terms "electromotive force" and "difference of potential" often exists and many times the term "potential" is used in cases where it is really inapplicable. In the previous section we used the idea of electrical level and showed how the voltage, $E$, of the electrical circuit corresponded to the difference in level in the hydraulic problem. When a quantity of water at a high level moves to a lower level it does work. When it is at the high level it has the *potentiality* for doing work; in other words, it possesses *potential energy.* Of course, the water will possess some potential energy when at the

lower level because there must still be lower levels to which it may fall. But the potential energy of the water will continually decrease as it moves to lower and lower levels.

*Potential as a Level.* Now the different levels may be said to be at *different potentials* because of the fact that the water, when at these different levels, possesses different amounts of potential energy. Instead of speaking of "the difference of potential energy possessed by unit quantity of water at two different levels" we might abbreviate the expression and merely say "the difference in potential" or "potential difference" of the two levels.

*Potential Difference.* We cannot speak of the level of any place unless we refer it to some other place. Ordinarily, sea level is taken as being zero and all other levels are referred to it. But, of course, everyone realizes that sea level is not zero; it merely serves as a reference surface.

These ideas obtained from the hydraulic problem may be applied directly to the electrical problem. We shall use the term "difference of potential," or "potential difference" of two points in an electric circuit, meaning the amount of work required to convey one coulomb of electricity from the point of lower electric pressure, or potential, to that of the higher potential. Just as the idea of the "level of a point on a hill" would be meaningless unless some reference point were used, so the word "potential" applied to any single point in an electric circuit is meaningless; we shall not speak of the "potential" of a point but of the *potential difference of two points* of the circuit.

Keeping in mind our original idea of electromotive force, we shall speak of the e.m.f. of a generator or cell; when considering two points in a circuit we shall speak of the "potential difference" between the two points. Thus we may say that a revolving armature *generates an e.m.f.*, and that between the two terminals of the machine *there is a potential difference* of so many volts. The two

terms are not synonymous. Thus a machine may be generating 100 volts in its armature while the difference of potential of its terminals may be only 90 volts.

**8. Magnetic Field; Law of the Magnetic Circuit.** All the space surrounding a magnet is said to constitute a **magnetic field.** The imaginary lines from the north pole of a magnet to its south pole really spread out and fill all space.

*Strength of Magnetic Field.* The strength of such a magnetic field is reckoned *in lines per sq.cm.* and a field is said to have unit intensity (one line per sq.cm.) when the field acts upon a unit magnetic pole with a force of one dyne at the point considered. The intensity of a magnetic field is usually represented by the symbol **H.** The field near a magnetic pole is comparatively strong but decreases rapidly in intensity with increasing distance from the pole.

The earth itself is a magnet and the field at the earth's surface acts upon a unit magnetic pole with a force of about 0.2 dyne. Such a field would be represented by one line for every 5 sq.cms. of area. The strength of field used in electrical apparatus is generally of a density of several thousand lines per sq.cm. A field of one line per sq.cm. is said to have an intensity of one **gauss.** The strength of field in the air gap of a generator might for example be given as 10,000 gausses.

*Continuity of Magnetic Lines of Force.* A magnetic line of force is always continuous, i.e., it closes on itself. A line of force may be traced from the north pole of a magnet, through an air space, into a piece of iron, through another air gap, then into the south pole of the magnet, and through the magnet to the north pole again, thus closing on itself and forming a complete loop. The path taken by this line of force may be called the **magnetic circuit.** The magnetic circuit of a generator for example would be through a pole into an air gap and so to the armature core, then

through the armature core, through another air gap and another pole, then through the yoke and so back to the original pole. This complete path is called the **magnetic** circuit of the machine.

*Magnetic Field due to Current in a Coil.* A coil of wire carrying a current generates what is called a **magneto-motive force** and this m.m.f. will produce a magnetic field through and around the coil. There is a definite relation between the total number of magnetic lines generated by the coil, the current and number of turns in the coil, and the constants of the magnetic circuit. This law of the magnetic circuit may be put in the form of an equation

$$\Phi = \frac{.4\pi NI}{\mathbf{R}}, \qquad (7)$$

where $\Phi$ = the total lines of force (or simply total *flux*) through the magnetic circuit;
$N$ = number of turns of wire in the magnetizing coil;
$I$ = current flowing in coil in amperes;
$\mathbf{R}$ = the reluctance of magnetic circuit.

*Reluctance.* The dimensions of the magnetic circuit may generally be determined fairly well and it is found that if the whole circuit is made of the same material (as for example of iron) we may write

$$\mathbf{R} = \frac{l}{\mu A}, \qquad (8)$$

where $l$ = the mean length of magnetic circuit in cms.;
$A$ = the average cross-sectional area of circuit in sq.cms.;
$\mu$ = a constant, the value of which depends upon the material comprising the magnetic circuit.

$\mu$ is called the **permeability** of the substance and is equal to one for all ordinary non-magnetic substances as air,

wood, paper, etc. For iron $\mu$ may have values between 50 and 12,000 depending upon the quality of the iron, the intensity to which it is magnetized, and its temperature. The permeability of iron as this material is ordinarily used in electrical machinery is about 2000.

If the magnetic circuit is made up of several parts in series, as is generally the case, the expression for reluctance will comprise several terms also.

Then we shall have

$$\mathbf{R}=\frac{l_1}{\mu_1 A_1}+\frac{l_2}{\mu_2 A_2}+\frac{l_3}{\mu_3 A_3}+, \quad . \quad . \quad . \quad . \qquad (9)$$

where the subscripts refer to different parts of the magnetic circuit.

**9. Magnetization Curves—Hysteresis.** The magnetic quality of a piece of iron is well shown by its **magnetization curve** (sometimes called *saturation curve*). This curve shows the relation between the magnetomotive force per cm. length (or ampere-turns per cm. of length) acting on a substance, and the density (i.e., lines per sq.cm.) of the magnetic flux which is produced in the substance. Flux density in substances which may be magnetized is usually represented by the symbol **B**.

*Use of Magnetization Curves.* Magnetization curves are extremely useful in calculating the necessary winding for the field coils of a machine. Knowing the flux density, B, required in a certain part of the magnetic circuit we can obtain at once from the magnetization curve the necessary ampere-turns per cm. of length; and this value multiplied by the length of that part of the magnetic circuit under consideration gives the ampere-turns required by that part of the circuit. The sum of the ampere-turns thus obtained for the separate parts of the circuit gives the total ampere-turns required for the magnetic path.

*Magnetization Curves for Iron.* By referring to Fig. 1, which gives the magnetization curves for cast iron, cast steel, and soft sheet iron, it is seen that for ordinary densities the soft sheet iron is much more permeable than either of the others. The cast iron is so much inferior to cast steel as a magnetic conductor that it is scarcely ever used. It

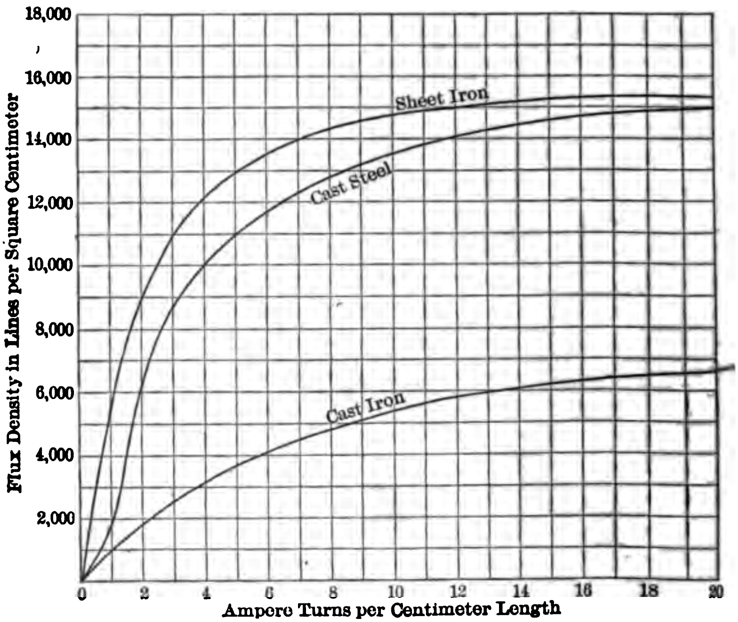


FIG. 1.—Magnetization Curves, or B-H Curves.

is seen by the shape of these curves that, after a certain density has been reached, the density does not increase very much even if the m.m.f. is doubled. When a large increase in m.m.f. produces but small increase in the flux density, the iron is said to be *saturated;* hence the name saturation curve.

*Permeability.* The permeability, $\mu$, is generally given as the ratio of the flux density to the m.m.f. per cm. length. It is therefore evident that $\mu$ may be obtained from the magnetization curve for any required density. A straight line is drawn from the point on the magnetization curve where the density has the required value, to the origin. The tangent of the angle between this line and the $X$ axis (i.e., the ratio of the vertical value for the point to the horizontal value) is evidently eqaul to $\mu$ because by definition

$$\mu = \mathbf{B}/\mathbf{H}, \quad \ldots \ldots \quad (10)$$

where $\mathbf{B}$ = the flux density in lines per sq.cm.,

$\mathbf{H}$ = the m.m.f. per cm. length.

For example, the permeability of cast steel when the density is 10,000 lines per sq.cm. as shown by the curve, Fig. 1, is $10{,}000/4.0 = 2500$. The maximum permeability will occur at that density which makes the line drawn through the origin tangent to the curve.

*Hysteresis.* If the iron is carried through a complete magnetic cycle, i.e., from zero to a positive maximum magnetization, then to zero, reversed, and to negative maximum, etc., the complete magnetization curve will form a loop as given in Fig. 2. This is called the *hysteresis loop* of the iron; its area is a measure of the amount of work used (in the iron) in carrying the iron through the cycle. The exact nature of the action involved in the dissipation of this energy is not known but it is supposed that the iron is made up of molecular magnets and that as these molecular magnets are reversed heat is generated by some sort of molecular friction.

*Occurrence of Hysteresis Loss in a Generator.* In the armature core of an electric generator or motor the magnetic flux is continually reversing its direction as the armature

revolves and so hysteresis loss must occur. That this is the case may be determined by measuring the amount of power required to rotate the armature core with and without a magnetic field on the machine. In a small generator a test showed that the power required to drive the armature around when the magnetic field of the machine was excited was 200 watts greater than that needed when there was no magnetic field. Practically all of this 200

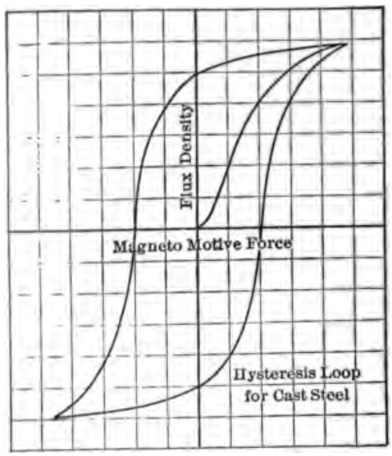


FIG. 2.—Hysteresis Curve for Steel.

watts of power was used up in the armature core as hysteresis loss; the heat due to this loss was sufficient to raise the temperature of the core several degrees.

To keep the hysteresis loss in a machine low, specially *annealed* iron or some special alloy steel is used. That steel giving the hysteresis loop of least area is the one which gives least hysteresis loss.

**10. Generation of E.M.F. in a Conductor Cutting Flux.** That an e.m.f. is generated in a conductor when it is so moved that it cuts the lines of a magnetic field was first

detected by Faraday. The laws of induced e.m.f. generally are not expressed in the form given above; they are based on the idea of a complete electric circuit in which the total number of lines of force is either increasing or decreasing. But it seems clearer and easier to consider any wire by itself. Is it generating an e.m.f. or not? Whenever the wire is *cutting flux* an e.m.f. is generated and the magnitude of this e.m.f. depends entirely upon the rate at which the magnetic flux is cut. *When the conductor moves through a magnetic field so as to cut* $10^8$ *lines per second, one volt of e.m.f. is generated in that conductor.*

*Magnitude of e.m.f.* If the length of a conductor is $l$ cms. and it is moving at a uniform velocity of $v$ cm. per sec. through a magnetic field of density **H** lines per sq.cm. and if the motion of the conductor is perpendicular to the direction of the magnetic field and to the length of the conductor, the e.m.f. generated in the conductor will be

$$\text{e.m.f. (in volts)} = lHv/10^8. \quad . \quad . \quad . \quad . \quad (11)$$

The necessity for stating the mutual perpendicularity of the motion, field direction, and length of conductor will be easily seen. Suppose that the conductor is moved in a direction parallel to the magnetic field; no flux will be cut by the conductor and so no voltage will be generated in it. Also if the conductor is moved in a direction parallel to its length no flux will be cut and so no e.m.f. will be generated. It sometimes happens in electric generators that the motion of the conductor is perpendicular to its own length but not perpendicular with the direction of the magnetic field. If the motion makes an angle $\theta$ with the magnetic field, the induced e.m.f. is given by the equation:

$$\text{e.m.f. (in volts)} = lHv \sin\theta/10^8. \quad . \quad . \quad . \quad (12)$$

In the armature winding of a dynamo-electric machine some of the conductors cut the magnetic flux and others (as for example, the end connections) do not cut any flux and so generate no e.m.f. when the armature is rotated. A distinction is sometimes made by calling those conductors of the armature in which an e.m.f. is generated **inductors**; the rest of the wires making up the winding are called conductors.

*Direction of the Induced E.M.F.* As has been said, an induced e.m.f. is always produced in a conductor where the conductor is so moved that it cuts magnetic flux. The direction of this induced e.m.f. is dependent upon the direction of the magnetic flux and the direction of the motion. A convenient rule which gives the direction of the induced e.m.f. is as follows: *Place the index finger of the right hand in the direction of the magnetic lines of force and the outstretched thumb in the direction of the motion; the middle finger, held at right angles to the index finger, will then indicate the direction of the induced e.m.f.* This, of course, will also be the direction of the current set up in the conductor on closed circuit.

**11. Force Exerted between a Magnetic Field and a Conductor Carrying Current.** If a conductor is placed in a magnetic field (not parallel to the direction of the field) and current is passed through the conductor, it will be found that the conductor and magnetic field so act on one another that a force is developed which tends to cause the conductor to move in a direction perpendicular to the direction of the magnetic field and to its own length.

*Direction of Force.* If the direction of the field is horizontal, then the conductor will be urged in a vertical direction when current is passed through it. Whether this force will be up or down will depend upon the direction of the current and the direction of the magnetic field. A rule which gives the direction of the force is as follows: If the index finger of the *right* hand is held pointing in the direction

of the lines of force of the field and the middle finger (held at right angles with the index finger) points in the opposite direction to the current, then the conductor will tend to move in the direction of the outstretched thumb.

If the direction of either is reversed the direction of the force acting on the conductor is reversed; if the direction of the current in the conductor and the direction of the magnetic field are both reversed, the direction of the force acting on the conductor remains unaltered.

*Magnitude of the Force.* The magnitude of the force depends upon the length of conductor perpendicular to the direction of the field, the amount of current sent through the conductor, and the density of the magnetic field in which the conductor is placed.

If $l$ = the length in cms. of the conductor perpendicular to the direction of the magnetic field;
$H$ = the strength of the magnetic field in gausses;
$I$ = the current through the conductor, in amperes;

Then,

$$\text{Force (in dynes)} = lHI/10. \quad . \quad . \quad . \quad . \quad (13)$$

If the total length of the conductor is $l'$ and the angle between the direction of the conductor and the magnetic field is $\theta$, $l = l' \sin \theta$; so that we may write

$$\text{Force (in dynes)} = l'HI \sin \theta/10. \quad . \quad . \quad (14)$$

If the force is desired in terms of English units we have

$$\text{Force (in pounds)} = .886 l'HI \sin \theta \times 10^{-7}, \quad . \quad (15)$$

where $l'$ is expressed in inches, $H$ in lines per sq.in. and $I$ in amperes.

*Application of Formula.* From the above formulæ the torque developed by any motor is easily calculated. If the strength of the motor field is known, and if the current flowing through the armature conductors and the total length of conductor on the armature which lies in the magnetic field are measured, the pull at the periphery of the motor armature is then obtained by formula (15). Then if the speed of rotation of the motor armature is known, the horsepower of the motor is easily calculated.

**12. Principles Involved in Operation of the Motor and the Generator.** A dynamo-electric machine is a machine which may be used to convert mechanical power into electrical power, or vice versa. A dynamo-electric machine which is made to revolve by the application of mechanical power, and which supplies electrical power to some outside circuit is called an *electric generator*, or merely a generator. A dynamo-electric machine to which is supplied electric power, causing it to revolve and furnish mechanical power to some load, is termed an *electric motor*, or merely a motor. In so far as their construction is concerned the two types of machine are practically identical. The same machine will often serve either purpose; a machine which, run as a generator, will give 5 kilowatts of electrical power at a voltage of 110 volts, would, if connected to a 110 volt supply line, run as a motor at about the same speed it previously had as a generator and would have an output capacity of about 5 horsepower.

Of course it must not be supposed that all machines which operate satisfactorily as motors will serve equally well as generators, or vice versa. Thus a motor of the type used in railway service (known as a series motor) might not operate as a generator at all; or at best its operation would be more or less unsatisfactory. Other types of machines, however, operate equally well for either purpose.

*Principle of the Generator.* The principle involved in the operation of an electric generator may be briefly stated

thus: *a conductor so moved through a magnetic field that it cuts lines of force will have induced in it an electromotive force.* As stated in section 10 the magnitude of this e.m.f. depends upon the rate at which the lines of the magnetic field are cut.

An electric generator, then, is a device for producing a magnetic field, in some manner or other, and having conductors so arranged that they may be moved through this magnetic field. Ordinarily the magnetic field is produced by a set of electromagnets and the conductors, in which the e.m.f. is to be generated, are placed on the periphery of a part of the magnetic circuit called the armature core, which is capable of rotation. When the armature core rotates, the conductors, which of course turn with it, are carried through the magnetic field produced by the electromagnets.

*Principle of the Motor.* The principle underlying the action of the motor may be stated thus: *If current is passed through a conductor which is placed in a magnetic field* (but not so placed that it is parallel to the direction of the field) *a force acts on the conductor tending to move it in a direction perpendicular to itself and to the direction of the field.* The magnitude of this force depends upon the strength of magnetic field, the strength of the current in the conductor, the length of the conductor, and the relative direction of the conductor and field.

*Reversibility of Generator and Motor.* In the motor, therefore, we must have a magnetic field and conductors so placed in this magnetic field that they may move. The magnetic field of the motor is generally produced by electromagnets and the conductors are placed on a part of the magnetic circuit, called the armature core, which is free to rotate. Thus the principle parts of the generator and motor are identical and a machine designed for one purpose may usually be used for the other.

In fact, in a power station where several generators

are used to furnish the output of the station, the driving power may be taken away from one of the generators, and it will continue to run, at practically the same speed it had before, but will be operating as a motor, taking electrical power from the other machines in the station. Thus the generator and motor are *reversible in their action.*

## CHAPTER II

### PARTS OF A DYNAMO-ELECTRIC MACHINE—FUNCTION MATERIAL, CONSTRUCTION

A dymano electric machine is a machine for converting mechanical energy into electrical energy or vice versa. It may be either a continuous current machine* or an alternating current machine. In the first part of this text we shall deal only with c-c. (abbreviation for continuous current) machines. A general classification of the parts of any c-c. dynamo electric machine may be made as follows:

(1) *Field Frame;* (2) *Armature Core;* (3) *Commutator;* (4) *Brushes and Brush Rigging;* (5) *Field Windings;* (6) *Armature Windings*. Each of these will be taken up separately, giving reasons for the different forms seen on various commercial machines, and showing why certain materials are preferable to others.

**13. Field Frame.** Fig. 3 represents the magnetic circuit of a simple *bipolar* machine and Fig. 4 shows the magnetic circuit of a *multipolar* machine. By the term field frame we mean that part of the magnetic circuit made up of the yoke and poles (and pole shoes if there are any). In continuous current machines that part of the magnetic circuit constituting the field frame is stationary, while that

* In speaking of machines for use in circuits where the current is uni-directional and non-varying the words *direct-current* and *continuous-current* are both used; either is correct and they are generally used synonymously—we shall use the term *continuous-current* as it seems to describe the nature of the current better than the term direct-current.

part named the armature core revolves when the machine is in operation. In an alternating current machine (taken

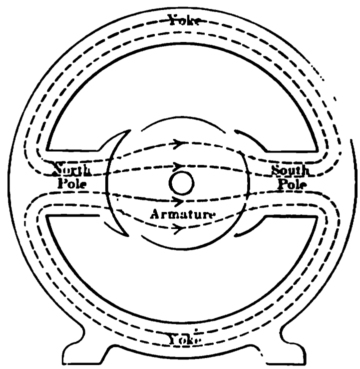


FIG. 3.—Sketch to Show Magnetic Circuits of a Bipolar Machine.

up in the later chapters) the field frame generally rotates while the armature is stationary. In either case it is seen

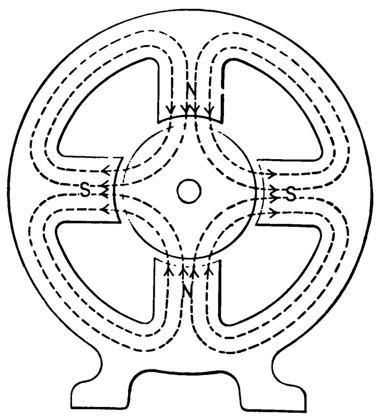


FIG. 4.—Sketch to Show Magnetic Circuits of a Four-pole Machine.

that the field frame is that part of the machine which carries the field coils through which current is passed to produce

the magnetic field. Fig. 5 shows a continuous current machine with a **stationary field** and Fig. 6 shows an alternator with a **rotating field.**

When the field frame has only two pole pieces (there must always be at least two), it is called a bipolar machine; practically all small motors and generators are of this form. Machines of 5 h.p. capacity and less are generally

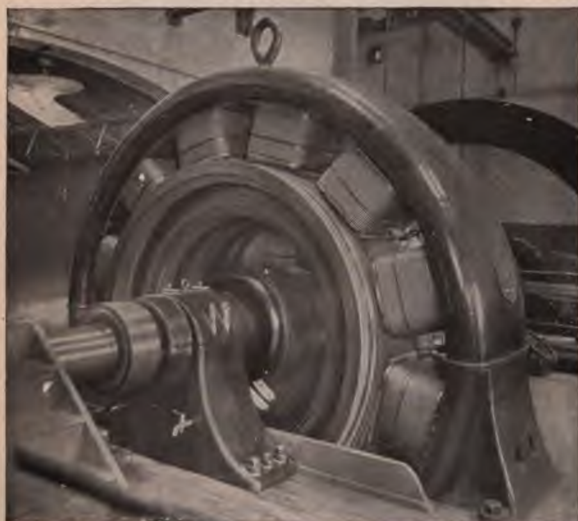

Fig. 5.—General View of a c-c. Machine, Showing Stationary Field and Revolving Armature.

bipolar; special high speed machines (driven by steam turbines) have been built bipolar in very large sizes. For generators or motors of ordinary speeds, above 10 h.p. in capacity, the multipolar form of field frame is generally used.

*Number of Poles.* The number of poles depends upon the capacity of the machine and the speed at which it is designed to operate. Of course the number of poles is

always even, as they go by pairs; for every north pole on a machine there must be a south pole. In large, low

FIG. 6.—General View of an a-c Machine, Showing Revolving Field and Stationary Armature. Westinghouse Elec. and Mfg. Co.

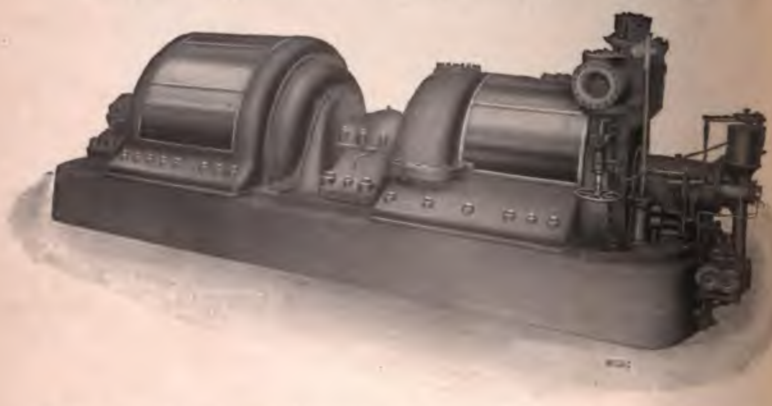

FIG. 7.—Turbo-driven Alternator, Showing Turbine and Generator on Same Bed Plate. General Electric Company.

speed machines the number of poles may be as high as 72 or more. With the introduction of the high speed turbine in place of the low speed reciprocating engine,

these large multipolar machines are being replaced by machines of 2 or 4 poles. Figs. 7 and 8 show the comparative sizes of two machines of about the same capacity.

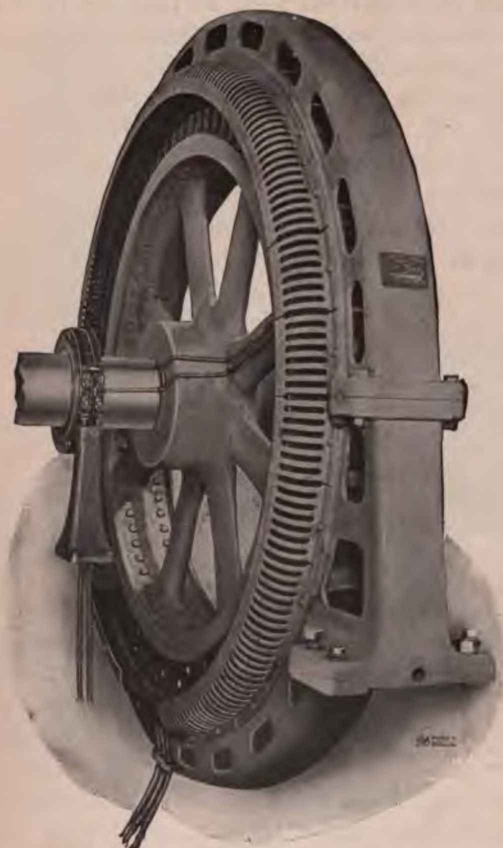

FIG. 8.—Alternator for Reciprocating Engine Drive. General Electric Company.

It is seen that the high speed **turbo-generator** (one designed for turbine drive) is much smaller and more compact than the older slow speed machine.

*Material for Yoke.* The material of which the field frame is made depends upon whether it is to be of the revolving or stationary type. When the field frame is stationary, cast steel is used at present; in the earlier types of machine, cast iron was used in building the field frame. Cast steel has much higher permeability than cast iron and so a higher flux density may be used with steel than with iron; because of this fact the field frame of steel, to carry a certain magnetic flux, is much lighter than would be the case if iron were used.

*Material for Poles.* The poles themselves are not cast as a part of the yoke except in the case of small, cheap machines. In discussing the design of field coils we shall show that it is advantageous to keep the cross-section of the pole as small as possible, and this makes necessary the use of laminated iron, which has higher permeability than any other kind. Most field poles are, therefore, built up of laminations, each about one-sixteenth of an inch thick, and are bolted to the yoke. Fig. 9 shows this construction.

FIG. 9.—A Laminated Field Pole.

*Field Frame for Alternators.* An alternating current generator generally has a revolving field; the field frame of such a machine designed for reciprocating-engine drive is made of a cast steel yoke and laminated steel poles, the same as a continuous current machine. The field frame for a turbo-alternator, however, is of special construction, being generally made from machine steel and having no projecting pole pieces. Because of the high speeds at which the revolving fields run, enormous mechanical strains occur and the field must be designed with this idea in mind.

The field coils of such machines are generally made in several narrow sections and imbedded in slots cut into the cylindrical shaped field. In Fig. 10 one of these field

FIG. 10.—Field Structure of a Turbo-alternator Designed to Withstand High Centrifugal Forces. Westinghouse Elec. and Mfg. Co.

frames is shown; it is seen that there are no projecting pole pieces and that the field coil is in sections.

*Leakage of Magnetic Flux.* The function of the field-coils and field frame is to produce a strong magnetic field

consideration of mechanical clearance* the only way to reduce the air gap reluctance is to increase its area and this is what the pole shoe does.

*Commutating Poles.* Besides the main poles, most modern c-c. machines have another set of poles which are very narrow compared to the main poles and are placed midway between the main poles; these small poles are to help commutation and are called **commutating poles.** A machine equipped with commutating poles is shown in Fig. 13; the extra poles are seen to be very narrow in

FIG. 12.—A Pole, to Show how a Pole Shoe may be Formed of the Laminations of Which the Pole Itself is Formed. Westinghouse Elec. and Mfg. Co.

comparison with the main poles. Another special field construction has been used on the *auxiliary-pole synchronous converter;* in this type of machine each main pole is split

* There are other factors affecting the length of the air gap besides that one mentioned here; as will be explained later the armature exerts a reaction on the magnetic field and the effect of this armature reaction is much exaggerated if the air gap is not of proper le[illegible] This armature reaction effect is really the factor controlling the le[illegible] of air gap. On some high-speed alternators, e.g., the air gap le[illegible] may be an inch or more and evidently mechanical considera[illegible] would not necessitate an air gap of such length.

in two parts and each part is wound separately. These machines may also be fitted with commutating poles but generally do not require them. An auxiliary pole converter without commutating poles is shown in Fig. 14.

**14. Armature Core.** As previously stated the magnetic circuit of any dynamo-electric machine may be considered as made up of two parts, one of which moves with respect to the other. The field frame, carrying the field windings

Fig. 13.—General View of a Field Frame to Show Commutating Poles. The field coils have been removed from one main pole and one commutating pole, to show the relative sizes of the two poles. General Electric Company.

has already been discussed; the other part of the magnetic circuit is called the **armature core.** On this part of the magnetic circuit are placed the conductors which serve to generate the e.m.f. (if the machine is a generator) or to carry the current by which torque is developed (if the machine is a motor).

*Lamination of Core.* The armature core is always made of laminated iron, that is, the core is built up by

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*Lamination of Core.* The armature core is always made of laminated iron, that is, the core is built up by

placing on the shaft a number of thin discs of iron and clamping them tightly together. The reason for making an armature core in this way, evidently much more difficult and expensive than if a solid piece of cast steel were used, will now be given.

FIG. 14.—A Special Construction of Field Frame. Each pole is made up of two parts, one being about twice as large as the other part. General Electric Company.

*Experiment to show the Advantage of Laminating the Core.* Two armature cores, of exactly the same dimensions, were made for an experimental generator. One of the cores was of solid iron and the other was of thin iron plates clamped together; thin paper was put between every other

plate. Then each armature core was in turn mounted in the field of the experimental generator and the power required to rotate these bare armature cores at 1200 r.p.m. with a certain strength of magnetic field, was measured. When the laminated core was tested it was found that the required power (excluding friction) was 9 watts; the core was left running for sometime but it remained cool. The solid core was then substituted for the laminated one and the power consumption was 350 watts; after running for a few minutes it became so hot that it had to be stopped, for fear of damaging the bearings. From this simple test we conclude that a solid armature core cannot be used in dynamo-electric machinery because, 1st, it requires so much power merely to rotate the armature core in the magnetic field, and 2d, the heat generated in the rotating core is so great that any windings on the armature core would be burned.

*Losses in Armature Core.* The heat generated in any piece of iron, rotating in a stationary magnetic field, is due to two effects, namely, *hysteresis* and *eddy currents.* It is evident that as the armature core rotates it is magnetized first in one direction and then in the opposite direction, as a point on the core moves from under a $N$ pole to a $S$ pole. In Chapter I the question of hysteresis loss in a piece of iron going through magnetic reversals was explained. There is then this hysteresis loss in an armature core and this loss may be kept small by using for the core iron that has a very narrow hysteresis loop, such as a specially treated alloy steel. After the sheet steel has been punched out in proper shapes for the core construction, these laminations are heated to a dull red heat and allowed to cool slowly. This process, called *annealing,* results in a steel having a very narrow hysteresis loop.

*Loss due to Eddy Currents.* Eddy currents (local currents in the material of the core itself) are produced in the rotating armature core because, as it moves through the magnetic

field, an e.m.f. is generated in it (*any conductor moving through a magnetic field so as to cut lines of force has an e.m.f. induced in it*); the direction of this e.m.f. is parallel to the shaft, i.e., lengthwise of the armature core. Under a $N$ pole it is in one direction and under a $S$ pole in the opposite direction. As the solid iron core may be considered as one large conductor it is evident that these e.m.fs. in the armature core will cause currents to circulate in the core. The direction of these currents is shown by Fig.

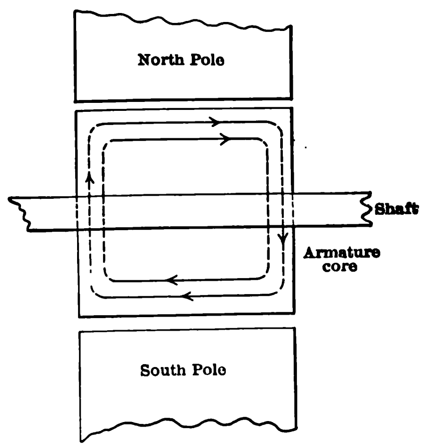


Fig. 15.—Path of Eddy Currents in a Solid Armature Core.

15, which represents a section of the core, taken parallel to the shaft. The direction of the e.m.f. induced in the core is shown by the solid arrows and the path of the eddy current is shown by the path formed by these arrows and the dotted lines.

*Reduction of Eddy Current Loss by Laminating the Core.* Now if the core is made of two parts, insulated from one another as in Fig. 16, the eddy currents will have to flow in two separate paths as shown. The resistance of each of

these paths may be assumed the same * as that of the path shown in Fig. 15 because that portion shown by the dotted lines is the same in both figures and this is the greater length of the path. The e.m.f. acting in one path of Fig. 16 is only one-half of that in the path of Fig. 15 and hence the current in one path of Fig. 16 will be one-half of that in Fig. 15. Hence the $I^2R$ loss per path will be one-quarter as large, but as there are two paths in Fig. 16 and only one in Fig. 15 the $I^2R$ loss in the divided core will be one-half as great as that in the ~~laminated~~ solid core.

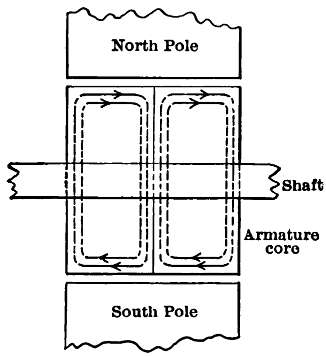


FIG. 16.—Eddy Current Paths when the Core has been Divided into two Parts.

If the division is carried further, the $I^2R$ loss due to eddy currents is still more reduced and by using very thin sheets this source of loss may be nearly eliminated. In commercial machines the laminations are generally 0.014″ thick. The laminations may be insulated from one another on large machines by a coat of insulating paint on each lamination; on small machines the oxide coating, formed on the iron sheet while it is being annealed, is relied upon

* This approximation is more nearly true as the thickness of the laminations is decreased.

for insulation. Sometimes thin paper is put between every few laminations to increase the insulation.

*Form of Laminations.* In small armatures the laminations are solid discs, merely having a hole in the center for the shaft. In multipolar machines it is unnecessary to use solid discs because in a large core made up of solid laminations, there would be more iron than is necessary for the magnetic flux. The paths of the flux in a multipolar machine is shown in Fig. 17. It is seen that the iron

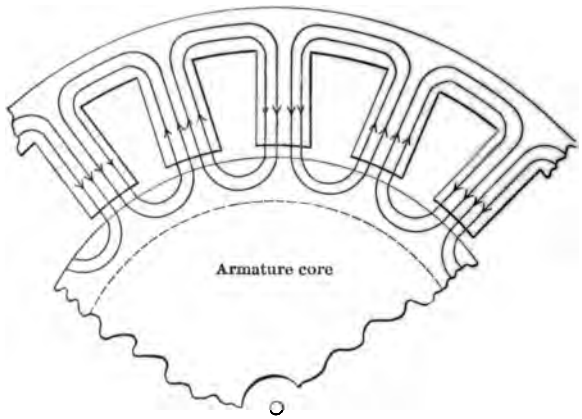


FIG. 17.—Hollow Discs are Used for Large Armature Cores. The magnetic flux would not penetrate very deep into the core even if it were solid.

inside the dotted circle is useless as far as the magnetic circuit is concerned.

The discs for large machines, therefore, are generally made ring-shaped; the iron which is punched from the inside of the disc may be used for the armature of a smaller. machine. If the armature is large (say more than 2 feet in diameter) the rings will not be in one piece; each lamination is made up of several pieces. In building up an armature core of such laminations, they are so assembled

that the joints in one lamination do not come opposite those in the adjacent one.

*Smooth and Slotted Cores.* In the early types of dynamo-electric machines the periphery (outside surface) of the armature core was *smooth* but in all modern machines the armature core is *toothed* (or *slotted*). In such a core there are a series of slots in the outer surface, running parallel to the direction of the shaft. These slots serve to hold the armature winding safely in place and also to reduce the effective length of the air gap of the machine.

By reference to Fig. 18 it is seen that the minimum length of air gap is fixed by the distance required for mechan-

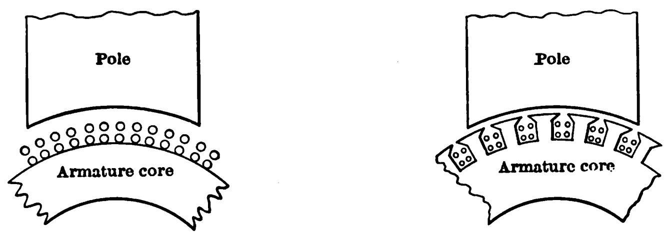


FIG. 18.—Smooth Core and Slotted Core.

ical clearance between the armature and the pole face plus the depth of the winding. In the toothed armature the effectiv length of the air gap is determined by the mechanical clearance distance only; as the armature teeth are good conductors for the magnetic lines, the only distance the magnetic lines have to go through air is that between the outside of the teeth and the inside of the pole face.

*Armature Spider.* The ring-shaped armature core must be fastened to the shaft in some way and for this purpose the **armature spider** is used. The spider generally consists of a cast-iron hub through which the shaft is fitted and from which radiates a set of spokes; on the ends of the spokes are lugs which are fastened by dovetailing keys to the

inside of the armature core. The armature punchings generally have dovetailed slots punched on their inside edge in such a fashion that when the core is assembled they line up with one another and form a set of dovetailed

Fig. 19.—Assembled Armature Core for Large c-c. Machine.

slots in the inside surface of the armature core, into which the keys in the spider fit.

In assembling such an armature the spider fitted with keys on the lugs is laid horizontal on the shop floor. Then the laminations, one at a time, are slipped over these keys

all the way around; when a complete ring of laminations has been placed, the next layer of laminations is put on in a similar manner, but so placed that the two rings "break joints," i.e., the joints between plates in the adjacent layers do not come opposite one another.

FIG. 20.—Assembled Armature Core for Large a-c. Machine. Westinghouse Elec. and Mfg. Co.

An armature core, assembled on its spider and fitted with shaft is shown in Fig. 19. This core is used in the construction of a large multipolar continuous current machine. The assembled armature core for a large alternating current generator is shown in Fig. 20. This armature is designed to be stationary; the field frame of the machine

consideration of mechanical clearance* the only way to reduce the air gap reluctance is to increase its area and this is what the pole shoe does.

*Commutating Poles.* Besides the main poles, most modern c-c. machines have another set of poles which are very narrow compared to the main poles and are placed midway between the main poles; these small poles are to help commutation and are called **commutating poles.** A machine equipped with commutating poles is shown in Fig. 13; the extra poles are seen to be very narrow in

Fig. 12.—A Pole, to Show how a Pole Shoe may be Formed of the Laminations of Which the Pole Itself is Formed. Westinghouse Elec. and Mfg. Co.

comparison with the main poles. Another special field construction has been used on the *auxiliary-pole synchronous converter;* in this type of machine each main pole is split

* There are other factors affecting the length of the air gap besides that one mentioned here; as will be explained later the armature exerts a reaction on the magnetic field and the effect of this armature reaction is much exaggerated if the air gap is not of proper length. This armature reaction effect is really the factor controlling the length of air gap. On some high-speed alternators, e.g., the air gap length may be an inch or more and evidently mechanical considerations would not necessitate an air gap of such length.

in two parts and each part is wound separately. These machines may also be fitted with commutating poles but generally do not require them. An auxiliary pole converter without commutating poles is shown in Fig. 14.

**14. Armature Core.** As previously stated the magnetic circuit of any dynamo-electric machine may be considered as made up of two parts, one of which moves with respect to the other. The field frame, carrying the field windings

FIG. 13.—General View of a Field Frame to Show Commutating Poles. The field coils have been removed from one main pole and one commutating pole, to show the relative sizes of the two poles. General Electric Company.

has already been discussed; the other part of the magnetic circuit is called the **armature core.** On this part of the magnetic circuit are placed the conductors which serve to generate the e.m.f. (if the machine is a generator) or to carry the current by which torque is developed (if the machine is a motor).

*Lamination of Core.* The armature core is always made of laminated iron, that is, the core is built up by

placing on the shaft a number of thin discs of iron and clamping them tightly together. The reason for making an armature core in this way, evidently much more difficult and expensive than if a solid piece of cast steel were used, will now be given.

Fig. 14.—A Special Construction of Field Frame. Each pole is made up of two parts, one being about twice as large as the other part. General Electric Company.

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plate. Then each armature core was in turn mounted in the field of the experimental generator and the power required to rotate these bare armature cores at 1200 r.p.m. with a certain strength of magnetic field, was measured. When the laminated core was tested it was found that the required power (excluding friction) was 9 watts; the core was left running for sometime but it remained cool. The solid core was then substituted for the laminated one and the power consumption was 350 watts; after running for a few minutes it became so hot that it had to be stopped, for fear of damaging the bearings. From this simple test we conclude that a solid armature core cannot be used in dynamo-electric machinery because, 1st, it requires so much power merely to rotate the armature core in the magnetic field, and 2d, the heat generated in the rotating core is so great that any windings on the armature core would be burned.

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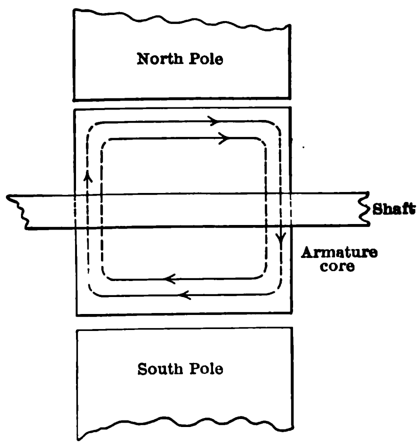


FIG. 15.—Path of Eddy Currents in a Solid Armature Core.

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*Reduction of Eddy Current Loss by Laminating the Core.* Now if the core is made of two parts, insulated from one another as in Fig. 16, the eddy currents will have to flow two separate paths as shown. The resistance of each of

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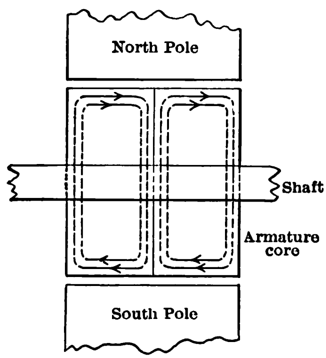


FIG. 16.—Eddy Current Paths when the Core has been Divided into two Parts.

If the division is carried further, the $I^2R$ loss due to eddy currents is still more reduced and by using very thin sheets this source of loss may be nearly eliminated. In commercial machines the laminations are generally 0.014″ thick. The laminations may be insulated from one another on large machines by a coat of insulating paint on each lamination; on small machines the oxide coating, formed on the iron sheet while it is being annealed, is relied upon

* This approximation is more nearly true as the thickness of the laminations is decreased.

to this external circuit reverses also, thus maintaining on the external line a uni-directional e.m.f.

*Construction of the Commutator.* The function and action of the commutator will be taken up in detail in

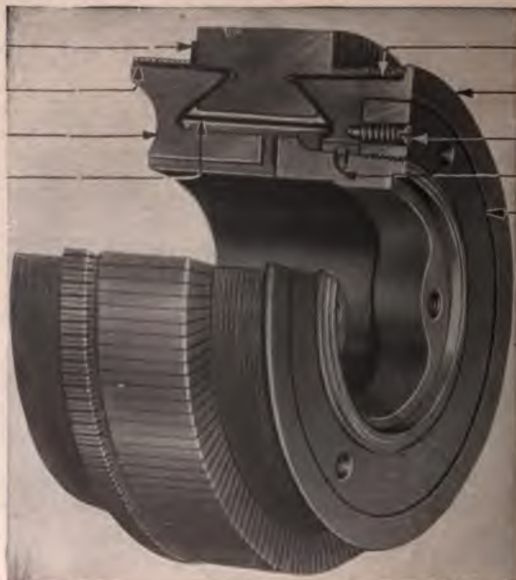

FIG. 26.—Commutator for Small 500-volt Motor. General Electric Co.

Chapter III; here we shall consider only the mechanical features of the commutator. It consists essentially of a set of copper bars, formed in such a shape that when assembled, they form a hollow cylinder. As they are assembled insulation is put betweem adjacent bars so that every bar is well insulated from every other. The commutator for a small machine is shown in Fig. 26, and Fig. 27 shows the assembled commutator of a large railway generator.

In taking up the construction of the commutator we shall consider the **bars** themselves, the **insulation** used in the commutator, and the **commutator spider,** which serves to clamp the bars together and hold them on the armature shaft.

*Form of bars.* The bars themselves are always made of copper, because it is a good conductor, is easy to shape

Fig. 27.—Commutator for Large Railway Generator, Showing Form of a Spider. The commutator and armature here shown are completely assembled. General Electric Co.

properly, and wears well. Generally these bars are stamped from copper rods, the cross-section of the rods being trapezoidal so that as the bars are assembled side by side they form a cylindrical ring. The bar for a medium

sized commutator is shown in Fig. 28. The end view, in (*b*), Fig. 28, shows the trapezoidal form of the bar; the angle between the two sides depends upon how many bars are to be used in the commutator. If there were to be 360 bars in the complete commutator this angle would be about 1°; if there were to be 720 bars it would be about one-half of a degree, etc.

*Insulation.* As the bars are assembled, sheets of insulation must be placed between every bar and its neighbor; also on the ends of the bar insulation must be used to

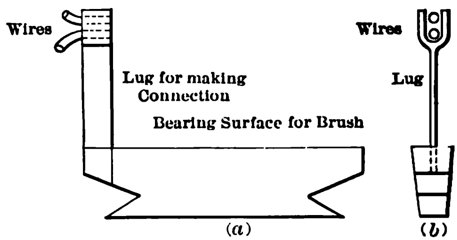


FIG. 28.—Sketch of a Commutator Bar.

keep it from contact with the spider, which clamps the bars together. For the insulation between bars a special grade of mica is always used; a grade of mica must be employed which has about the same wearing qualities as the copper bar itself. If the mica should be too tough and wear away more slowly than the copper, the mica insulation would soon project above the copper bars and would cause sparking at the commutator.

The ability of mica to stand high temperature without deterioration makes it preferable to any such insulation as fiber, oiled cambric, etc. These substances are good insulators when kept cool and dry but commutators frequently become very hot when the machine is operating and also sparking is likely to occur where the brushes bear

on the commutator; under such conditions these insulators would become charred and thus spoiled in so far as their insulating qualitites are concerned.

Where the spider clamps the assembled copper bars, insulation must be used to insulate the bars from the spider. Ring-shaped pieces, with V-shaped cross-section, are required for this purpose. Mica sheets are very brittle and could not be bent into the proper shape for such use, so **micanite** is generally used. This is made by cementing very thin, small sheets of mica together by some such flexible binder as shellac. The thin flakes of mica are laid

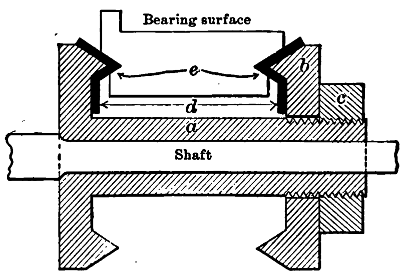


FIG. 29.—Cross-section of a Small Commutator, Showing the More Essential Parts of the Assembly. General Electric Co.

in the bottom of a tray to an even depth (perhaps one-sixteenth of an inch) the thin shellac poured in and allowed to drain off. By a proper drying and compressing process a flexible sheet of micanite is obtained which, when warmed, may be formed into any desired shape.

*Spider*. The commutator spider is made of cast iron in two or three pieces. The assembly view of a small commutator is shown in Fig. 29. The spider, shown in cross-section, is seen to consist of a sleeve, *a*, that fits on the armature shaft, a loose end ring, *b*, and the lock nut, *c*. The sleeve, *a*, is pinned to the shaft when the commutator

has been placed in its proper position. The micanite rings are shown at *d*. If the commutator has been properly assembled the two surfaces marked *e* receive all the pressure as the lock nut *c* is tightened; in this way the lock nut serves not only to tighten the commutator bars endwise, but also to squeeze them tightly together sidewise by forcing them into a cylinder of smaller radius.

*Number of Bars.* The number of bars to be used in a commutator depends principally upon the voltage for which the machine is designed. The function of the commutator is to change the alternating e.m.f. of the armature coils to a unidirectional e.m.f. on the external circuit. If too few bars are used in the commutator the line e.m.f. will be unidirectional but will not be constant in value i.e., it will be a pulsating e.m.f. If as many as 12–16 bars are used between brushes, these pulsations are so small as to be negligible.

If a two pole machine had only 8 bars in its commutator, the amount of variation in the line e.m.f. would be about 4%, hence this number of bars would be too small for ordinary use. For an electroplating generator, however, the pulsation would not be disadvantageous and plating machines generally have very few commutator bars. The number of bars to be used on railway generators or lighting generators etc. is fixed by the rule that *the voltage between adjacent bars should not be greater than 10 volts.* Now as the full voltage of the machine exists between adjacent sets of brushes this means that the minimum number of bars $= \dfrac{\text{voltage of machine}}{10} \times$ number of sets of brushes.

This rule is only approximate for many reasons. The voltage between adjacent brushes is not distributed uniformly among the commutator bars between the same brushes. Between a pair of adjacent bars on the commutator midway between two sets of brushes the e.m.f.

may be 15 volts and at the same time two bars near one set of brushes may have a difference in voltage of only one or two volts. The above formula considers only the *average voltage* between bars and so gives the *minimum* number of bars that should be used.

*Effect of Using too Few Bars.* Between adjacent bars of the commutator the mica insulation is generally about 0.02″ thick and such a thickness of mica will stand a pressure of perhaps 10,000 volts so that the limit of 10 volts per bar is evidently not fixed by the dielectric strength of the mica. The difficulty which arises if the voltage per bar gets too high is caused by *current leaking over the surface of the mica insulation.* The surface of the mica becomes soaked with oil and if this oil carbonizes it becomes a fair conductor. Even if there is no carbonized oil on the surface of the mica, there will always be more or less dust rubbed into it, and also the whole surface of the commutator may become coated with a thin layer of oil and dust. If the voltage per bar is too great under such conditions, current leaks over the surface of the commutator from one brush to the next and a "flash-over" may occur; i.e., a short circuit may occur between a pair of brushes, the short circuit current following the surface of the commutator.

**16. Brushes and Brush Holders.** As the commutator, to which the armature coils are attached, revolves with the armature, it is necessary to have some stationary conductors for making a rubbing contact with the moving surface of the commutator, the external circuit being connected to these stationary conductors. Such conductors are called **brushes;** they are generally made of *carbon blocks,* but may sometimes be made of *copper leaves, copper gauze,* etc. The choice between copper and carbon depends entirely upon the voltage for which the machine is designed. A low voltage machine, such as is used in electroplating, must be equipped with copper brushes; carbon

brushes would not serve at all. For machines of voltages of 100 and more carbon brushes must always be used.

*Contact Area of Brushes.* The brushes and commutator form a moving contact surface across which all of the current which flows from the armature to the external circuit must pass. To keep this contact surface in good condition, i.e., smooth and free from dirt, requires more care than any other task connected with the operation of dynamo-electric machinery. The area of the brush where it comes in contact with the commutator surface is called the **contact area** of the brush.

*Safe Current.* The current which can be carried safely by a square inch of contact area depends upon the two materials forming the contacting surfaces. If a copper brush is bearing on the commutator surface and the brush has one sq.in. of contact area, 150 to 200 amperes may safely be carried from the commutator by the brush; if the brush is made of carbon and has one sq.in. of contact area, not more than 40–60 amperes may be safely carried. If these values are exceeded, the brush and commutator will get too hot.

If either the commutator or brush surface becomes rough, the contact area is very much diminished. If a piece of dirt works into the contact surface of a brush and so makes a projection on this surface, it is evident that the brush will touch the commutator only at this projecting place unless the brush is very *flexible.*

*Flexibility of Brushes.* A brush made of copper leaves or wires is very flexible while one made of a carbon block is not flexible at all. So that if a slight projection on the commutator lifts off from the commutator one part of a copper brush contact surface, the rest of the brush may stay in contact with the commutator owing to its flexibility. But if one corner of a carbon brush is lifted from the commutator, the whole brush leaves the commutator surface and the circuit is practically opened.

If the machine is delivering current to the external circuit when this happens, sparking will occur at the commutator surface and if this occurs for any length of time the surface of the commutator becomes so roughened as to be unserviceable. In so far as flexibility is concerned, therefore, copper is preferable to carbon. The non-flexibility of the carbon brush is partly overcome by using instead of one big brush, several small brushes, each capable of movement separately. Then, as one of these small brushes is lifted from the commutator accidentally, no open circuit is produced because the rest of the small

FIG 30.—Five Small Brushes, instead of One Large One, are Here Used to Obtain Flexibility in the Brush as a Whole. Allis-Chalmers Co.

brushes are still making contact. Fig. 30 illustrates this construction; on the one brush holder stud there are mounted five separate brushes, each of which is free to move by itself.

*Brush Holders.* As the brush (whether copper or carbon) wears away with use, some arrangement must be made to feed continually the brush toward the commutator so that the proper pressure between the brush and the commutator is always maintained. The device by which this is accomplished is called the **brush holder.** It is a sort of clamp, through which the brush is capable of motion, and is mounted on the **brush holder stud.** This motion

of the brush is produced by a spring fastened tightly on one end to the brush clamp; the other end of the spring presses directly on the brush itself. There may be several brush holders on the same stud. On large machines as many as twelve or more may be used; there are seldom less than two because one carbon brush has no flexibility and sparking is likely to result if only one is used.

*Number of Sets of Brushes.* There must be at least two brush holder studs, one at which the current leaves

FIG. 31.—A Common Type of Brush Holder, Showing Brush in Place General Electric Co.

the machine and another at which it enters. With the type of armature winding commonly employed, as many sets of brushes (i.e., groups of brushes on the same stud) are required as there are field poles. A 12-pole generator would have 12 brush holder studs, mounted rigidly on the **brush yoke;** the studs would be equally spaced on the yoke and insulated from it; every other stud would be connected together and the two sets of studs so formed could be connected to the two terminals of the generator.

In Figs. 31 and 32 are shown two types of brush holders,

and Fig. 33 shows the complete brush rigging of a small c-c. generator.

*Superiority of Carbon for Brushes.* It has been said that carbon brushes are used on all machines except those designed for electroplating and this in spite of the fact that copper is a better conductor than carbon and only requires about one-quarter as much contact surface for a given current. There are two important reasons why carbon is preferred to copper for brushes: 1st, the mechanical wear on the commutator is much less with carbon than with copper; 2d, it is practically impossible to obtain

Fig. 32.—Brush Holder for Railway Motor. Westinghouse Elec. and Mfg. Co.

sparkless commutation when copper brushes are used on any but low voltage machines.

*Sparkless Commutation.* The commutation is said to be sparkless, or "black," when no sparking takes place at the contact surface between the brush and commutator. It is very important that sparkless commutation be obtained because under the action of sparking at the brush contact, the commutator very quickly roughens, which makes the sparking worse and so the machine is soon rendered unfit for service. The explanation of this effect (i.e., sparking produced by copper brushes) will be taken

up in a later chapter. It must be borne in mind here, however, that the sparking with copper brushes is not due to such causes as rough commutator, etc.; no matter how smooth the commutator may be or how well fitted the brushes may be, this sparking cannot be eliminated.

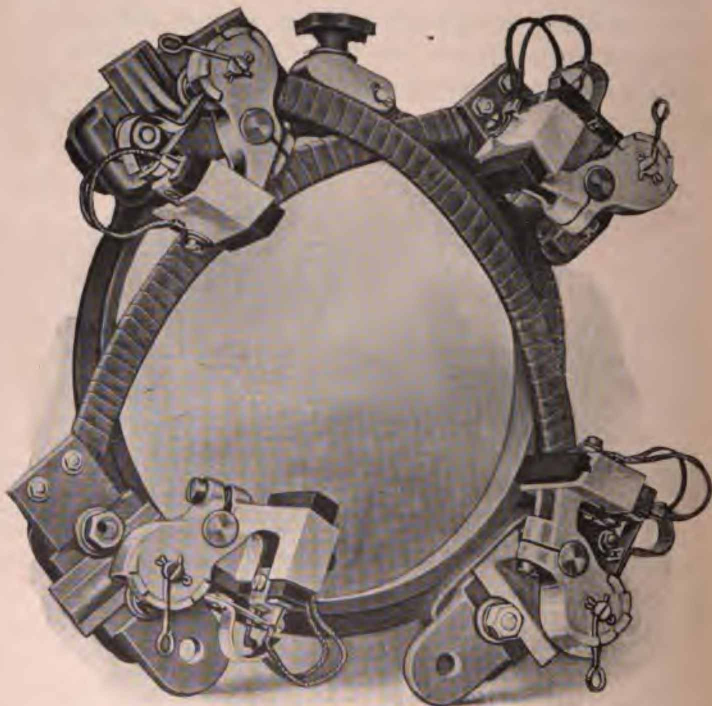

FIG. 33.—Complete Brush Rigging of a Small c-c. Machine. Westinghouse Elec. and Mfg. Co.

*Pressure of Brushes.* The springs on a brush holder are adjustable so that the pressure exerted by a brush on the commutator may be varied as desired. If too little pressure is used, the contact is not good and the electrical resistance

of the contact becomes high, hence the $I^2R$ loss at this place becomes too great and the brush will overheat. If too much pressure is exerted by the brush on the commutator, the power used up due to mechanical friction of the brushes becomes too great and the brushes and commutator will get hot from this cause. It has been found that with carbon brushes the best results are obtained when the springs are adjusted to give a brush pressure of about 1.4 lbs. per sq.in. of contact surface; this value may, however, be anywhere between 1 lb. and 5 lbs., depending upon the brush, speed, etc.

*Resistance of Brush Contact.* The resistance of the contact surface of a carbon brush and commutator is a variable depending upon the current density at the contact surface. As the current density increases the resistance decreases; the variation of the resistance with the current takes place in such a manner that the *IR drop at the contact surface is nearly constant, and not dependent upon the current.* While this *IR* drop is slightly different with different types of brushes and with the different grades of carbon employed, it is safe to assume that on the average c–c. machine, with the commutator in good condition, the drop is *one volt per brush contact.* As there are always two brush contacts in series the *total brush contact resistance drop in any c–c. machine is about two volts.*

*Brushes on Low-voltage Machines.* It is because of this contact resistance drop that carbon brushes are never used on very low-voltage machines. We shall show in a later chapter that the efficiency of any electric generator must be less than the ratio of the terminal voltage to the generated voltage.

$$\text{The terminal voltage} = E_g - IR_a, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

where $E_g$ = the generated voltage of the machine;

$IR_a$ = the total " drop " in the armature circuit (always greater than the brush contact resistance drop);

If carbon brushes are used on the machine, we must put

Efficiency is less than

$$\frac{E_g - 2}{E_g}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (17)$$

Now if $E_g$ is, say, 6 volts, the efficiency of the generator would have to be less than 66% ; as a matter of fact, it would probably be about 40%. On higher voltage machines this drop of 2 volts at the brush contacts is not such an important factor in determining the efficiency.

**17. Field Windings.** The field windings of a dynamo electric machine serve to force the flux through the whole of the magnetic circuit. The field coils are always placed on the poles; the m.m.f. produced by these field coils must be sufficient to force the magnetic flux through the poles, yoke, air gaps, and armature core. If the length, area, and permeability of each portion of the magnetic circuit are known, the number of turns required in one field coil and the current necessary can easily be calculated.

*Ampere-turns.* The term ampere-turn will be used frequently in our discussion; its significance is easily seen by a few illustrations. A coil of 50 turns in which a current of 2 amperes is flowing has 100 ampere-turns; a coil of one turn having a current of 100 amperes has 100 ampere-turns; a coil having 2000 turns in which a current of 0.8 ampere is flowing has 1600 ampere-turns. *The number of ampere-turns of a coil is equal to the product of the number of turns in the coil and the current flowing in the coil.*

Referring to formulas (7) and (9), pp. 16 and 17, we may write

$$\Phi = \frac{.4\pi NI}{\dfrac{l_1}{A_1\mu_1} + \dfrac{l_2}{A_2\mu_2} + \dfrac{l_3}{A_3\mu_3}}. \quad . \quad . \quad . \quad . \qquad (18)$$

Substituting in this equation the proper values for the various lengths, areas, and permeabilities, and knowing the required flux, $\Phi$, the number of ampere-turns which will be necessary is found at once by solving for $NI$. Knowing $NI$ we can use as many turns as we like providing the proper current is used to make the product $NI$ the required amount.

*Determination of Ampere-turns Necessary.* This method of determining the size of the field coil is almost never used

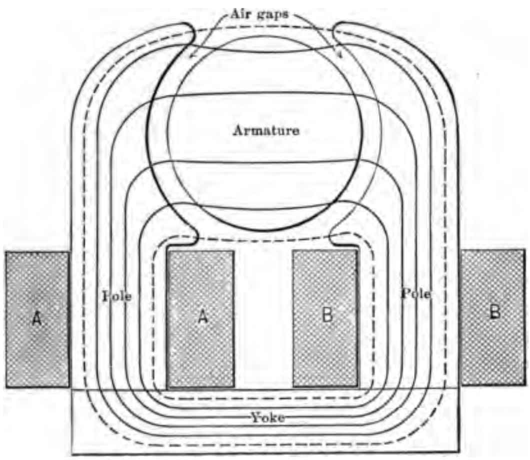


FIG. 34.—Magnetic Circuit of a Small Old-style, Bipolar Machine. Field coils shown by hatched area.

because a much simpler method is available. Let us consider a bipolar field frame of the shape given in Fig. 34. The magnetic circuit consists of the yoke, two poles, two air gaps, and the armature core all in series. The field is to be excited by two coils shown in section at $A$ and $B$. These two coils give m.m.fs. which act in the same direction on the magnetic circuit. We will figure the ampere-turns required for the whole circuit as though only one coil was to be used;

one-half this number will be the proper number of ampere-turns per coil.

The **B–H** curves given on p. 18 are to be used in this calculation. These curves are plotted between *flux density* and *ampere-turns per cm. length* of the magnetic circuit. Suppose that a ring of cast iron is to be magnetized to a flux density of 5000 lines per sq.cm. and that the average length of the magnetic path in the ring is 75 cm. How many ampere-turns will be required?

By reference to the magnetization curve for cast iron it is seen that to produce a flux density of 5000 lines per sq.cm. 9 ampere-turns are required *per cm. of length of the path.* As the length of the path is 75 cm. the number of ampere-turns required is $75 \times 9 = 675$ ampere-turns.

*Field Coil Calculation.* This same method may be used for calculating the necessary ampere-turns for the magnetic circuit of the machine shown in Fig. 34.

Suppose the necessary flux through the armature core is 1,600,000 lines. There must be through the poles and yoke more flux than this because of the *leakage lines.* If the leakage factor is taken as 1.25 the flux through the yoke and poles is $1{,}600{,}000 \times 1.25 = 2{,}000{,}000$ lines.

The cross-sectional area of the different parts of the magnetic circuit would be given. The average length of the magnetic path in each part may be estimated. From the flux and cross-section the density in each part is calculated and then from the magnetization curves the ampere-turns per cm. are obtained; this quantity multiplied by the length of path in that part of the circuit gives the required ampere-turns for that part. The sum of the ampere-turns required for each part gives the number required for the complete magnetic circuit and one-half this number are to be put in each field coil.

The number of ampere-turns required for the air gaps cannot be obtained from the curve sheet but is easily calculated as follows;

$$\Phi = \frac{.4\pi NI}{\frac{l}{A\mu}}$$

and for air $\mu = 1$.

Transposing
$$\frac{\Phi}{A} = B = .4\pi \frac{NI}{l} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

or
$$\frac{NI}{l} = \frac{B}{.4\pi} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

The ampere-turns required per cm. of air gap is therefore equal to the flux density in the air gap divided by $.4\pi$. In calculating the magnetic circuit it is convenient to tabulate the data as shown below:

| Part. | Material. | Average Length in cm. | Area in sq. cm. | Flux. | Flux Density. | Amp.-turns per cm. | Amp.-turns. |
|---|---|---|---|---|---|---|---|
| Yoke.... | Cast iron . | 35 | 350 | 2000000 | 5720 | 12 | 420 |
| Poles.... | Cast steel. | 30 each | 200 | 2000000 | 10000 | 3.8 | 228 |
| Air gap... | Air...... | 0.2 each | 250 | 1600000 | 6400 | 5095 | 2038 |
| Armature. | Laminated iron.... | 25 | 225 | 1600000 | 7120 | 1.5 | 37 |

Total ampere-turns required........................ 2723

Ampere-turns to be used per coil $= \frac{2723}{2} = 1362$

We will next figure the necessary ampere-turns for a small modern bipolar machine with a slotted armature and double yoke. In this yoke the flux from the pole divides, half going one way and half the other. The flux in going through the armature teeth is very dense and although the length of path is small it is better to figure this as a separate part of the magnetic circuit, instead of treating the teeth as part of the armature core.

A diagram of the magnetic circuit is given in Fig 35, showing the location of the field coils, leakage lines, etc. The poles are made of laminated iron and are bolted to the cast-steel yoke. The area of the teeth is taken as the cross-sectional area of as many teeth as lie under the pole

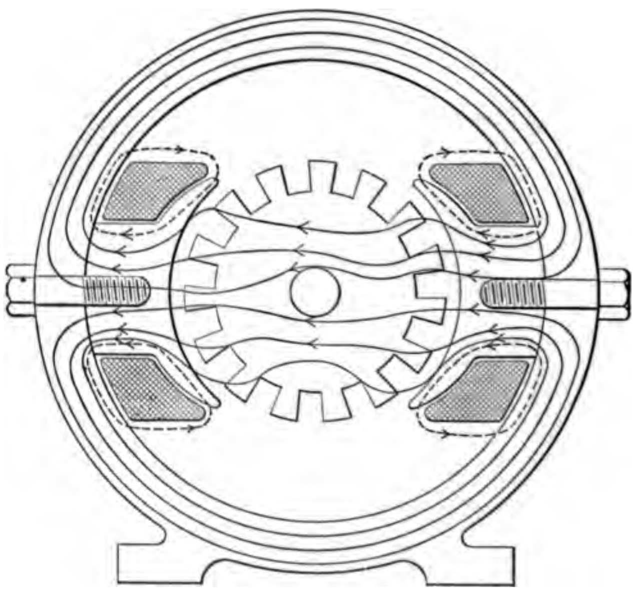

FIG. 35.—Magnetic Circuit of Small, Modern, Bipolar Machine. Field coils shown by cross-hatched area: leakage lines shown dotted.

face. Practically all the flux leaving the pole face crowds into the teeth, very little of it going down to the armature core by the slots. The leakage factor for the machine umed to be 1.15; if the required armature flux is 00 lines the flux through the poles and yoke is then 00 lines.

The pole shoe serves to increase the area of the air gap so as to reduce the density in this part of the magnetic circuit. Tabulating our data as before, and using the magnetization curves, we have:

| Part. | Material. | Length in cm. | Area in sq. cm. | Flux. | Flux Density. | Amp.-turns per cm. | Amp.-turns. |
|---|---|---|---|---|---|---|---|
| Armature. | Laminated iron | 15 | 100 | 1200000 | 12000 | 4 | 60 |
| Teeth.... | Laminated iron | 1.2 cm. on each side | 70 | 1200000 | 17150 | 95 | 228 |
| Air gap... | Air...... | 0.25 cm. each | 120 | 1200000 | 10000 | 7975 | 3987 |
| Poles.... | Laminated iron | 10 cm. each | 90 | 1380000 | 15350 | 17 | 340 |
| Yoke.... | Cast steel. | 50 | 60 each | 1380000 | 11500 | 5 | 250 |

Total ampere-turns required..................... 4865

$$\text{Ampere-turns per pole} = \frac{4865}{2} = 2433$$

These two examples will serve to show how the number of field ampere-turns is roughly determined. In an actual design other factors have to be taken into account; the effect of the armature m.m.f. on the field strength has to be considered and the problem is somewhat more complicated than we have indicated.

*Proper Size of Wire.* The size of wire to be used in winding the field coils is now to be determined. Generally, all of the field coils of the machine are connected in series and then to some source of e.m.f. from which the field current is to be taken. The average length of one turn of the field coil is estimated from the known size of the field pole and the assumed depth of the coil. Suppose that the length of one turn close to the field pole was 10 inches and that we assume a winding depth of one inch; the length of

an outside turn would be in the neighborhood of 18 inches (if the pole were of rectangular cross-section) so that the *average length* of a turn would be 14 inches.

Let $E$ = the voltage of the field current supply;
$NI$ = the total ampere-turns required on the machine $= NI$ per pole $\times$ number of poles;
$l$ = the average length of one turn, in feet;
$r$ = the resistance per foot of the proper sized wire; this is to be determined;
$I$ = the current through the field circuit;
$R$ = the resistance of the field circuit;
$N$ = the total number of turns on all coils in series.

Then,

$$R = Nlr, \qquad (21)$$

and

$$I = \frac{E}{R} = \frac{E}{Nlr}, \qquad (22)$$

multiplying both sides by $N$

$$NI = \frac{NE}{Nlr} = \frac{E}{lr},$$

or

$$r = \frac{E}{lNI}. \qquad (24)$$

Now $NI$ has been calculated, $E$ is known, and $l$ has been approximately determined from the assumed size of the field coil. Therefore, $r$, the resistance per foot, of the proper sized wire to use, is determined. From the wire table the diameter of the wire and its cross-sectional area in circular mils can be obtained.

Knowing the proper sized wire and the number of required ampere-turns, the proper number of turns is now

to be determined. Here we at once notice a peculiarity in the problem. *So far as the magnetizing effect of the coil is concerned, with a given supply voltage, it makes no difference how many turns are used for the field coil; no matter how many turns are used the m.m.f. of the coil will be the same.*

Suppose that we put on 1000 turns and that this number of turns has a resistance of 50 ohms. If the voltage of the field current supply is 100 volts the field current will be 2 amperes and the ampere-turns of the coil will be 2000. If, now, 2000 turns are used the resistance of the coil increases to 100 ohms, the field current decreases to one ampere and the ampere-turns in the coil will be 2000 as before.

*Proper Number of Turns.* There must be some method of determining the proper number of turns to use; *and this is fixed by the safe allowable temperature rise in the coil.* It is apparent that if, for example, only one turn were used in the field coil, the proper number of ampere-turns would be obtained but the current through the one turn would be so great that the wire would melt. As the number of turns is increased, the required current decreases; when the number of turns has been increased to such an extent that the current which flows through the coil does not heat the wire more than 50° C. above room temperature (the limit fixed by the A.I.E.E.), we may say that the field coil has been properly designed.

The process of predicting the temperature rise from the power used up as heat in the coil ($I^2R$ loss in the coil) and the calculated radiating surface requires judgment and experience, because some radiating surfaces are more effective than others, etc.

It has been found, however, from the results of many tests that a safe figure to use in fixing the number of turns is obtained by allowing 1200 *circular mils per ampere* in the winding. The proper sized wire has already been found and so the cross-section in circular mils is known. Suppose

it was 2400 circular mils; this wire could safely carry 2 amperes so that if 3000 ampere-turns were required per pole the proper number of turns = 3000/2 = 1500 per coil. The figure 1200 circular mils per ampere, is good only for field coils where the wires are packed tightly together and the heat cannot easily escape. In armature windings, where the ventilation is better, it is customary to allow 750 circular mils per ampere, and if the wire were stretched in the open, probably 200–300 circular mils would be a sufficient allowance.

*Construction of Field Coils.* The kind of wire to be used in making a field coil and the method of winding it depends upon the machine for which it is to serve. For small machines double cotton covered wire or enamel covered wire is wound on a properly shaped wooden form. It is then taken off and taped, and then dried and impregnated with some insulating compound. When cold the coil is ready for assembly on the machine.

For practically all revolving fields, copper ribbon is used. This is wound on the spool edgewise. Only one layer of winding is used so that each turn has an edge exposed to the outside air. This construction serves to more readily cool the winding, and, therefore, less than 1200 circular mils per ampere is required for ribbon wound coils. Another reason for using ribbon, wound edgewise, on revolving fields is that a field coil must be mechanically strong to stand the centrifugal force exerted on its outer edge (where it comes in contact with the pole shoe) when the field is revolving. The ribbon wound coil stands this strain easily even on very high speed machines while a wire wound coil might possibly crush under the excessive pressure due to centrifugal force.

The copper ribbon used for these field coils is insulated by attaching a strip of paper on one side only, this being sufficient to keep the adjacent turns from touching one another. The outside edge has on it no insulation at all,

hence the heat generated in the ribbon can readily escape to the air. In Fig. 36 is shown a view of a wire wound

FIG. 36.—Wire-wound Field Coil. General Electric Co.

field coil and Fig. 37 shows a ribbon wound field coil; the ribbon has been allowed to uncoil partially so that the method of winding may be apparent.

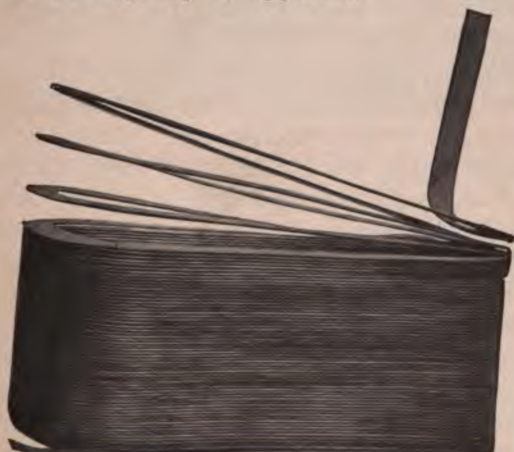

FIG. 37.—Ribbon-wound Field Coil. General Electric Co.

**18. Armature Windings.** The question of armature windings is a very broad one and we can give here only an

elementary outline and analysis of some of the various forms employed in different c-c. generators. By the term "armature winding" is meant the group of conductors placed on the armature core, which revolve with it and cut the magnetic field. The different ways in which these conductors may be placed on the armature core and interconnected, leads to innumerable winding schemes. The armatures of motors and generators are wound in exactly the same way; the same factors have to be kept in mind no matter whether the armature is to be used for one purpose or the other. We shall speak of the different windings as generator windings but they serve just as well for a motor armature.

*Classification of Armature Windings.* The armature windings for alternating current generators are quite different from those intended for a c-c. generator; we shall consider here only the c-c. windings, the first two general divisions of which are the **ring winding** and the **drum winding.**

*Ring Winding.* In the ring winding the coils are wound around the armature in such a way that half of the coil is on the *inside of the armature core.* This may be seen by reference to Fig. 38, which shows the armature of an early type of generator. The winding of these armatures is not as easy as the winding of a drum armature but a more important objection is the amount of "dead wire" on the armature.

*Disadvantage of the Ring Winding.* The conductors on the inside of the core do not cut any flux as the armature revolves and hence they can generate no e.m.f. This extra wire is detrimental to the machine not only because of the extra cost for wire but because the *resistance of the armature winding is much larger* than it should be; this ''ʼı resistance means high $I^2R$ and a high heat loss in the ɿtor. As a result the efficiency is lowered.

.e ring winding is used very little at present and we

shall not discuss it further except in connection with the Thomson-Houston arc generator which illustrates another type of winding.

The drum winding is not easy to show by a diagram however and so we shall, in analyzing the action of a drum winding, often picture the drum winding as a ring winding. The ring winding is easier to represent and the deductions we make regarding its action apply equally well to the drum winding.

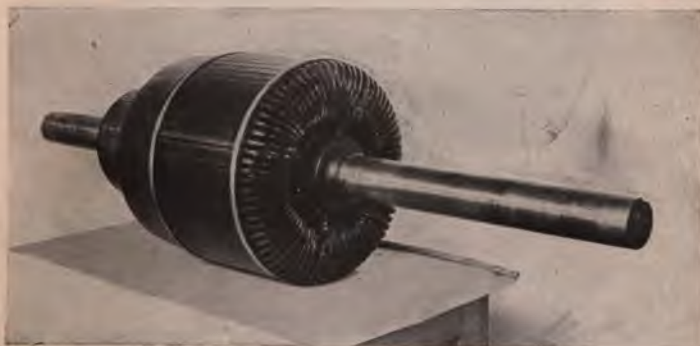

FIG. 38.—View of a Ring-wound Armature (Early Type). Crocker-Wheeler Co.

*Drum Winding.* The drum winding is distinguished by the fact that all of the armature conductors *are on the outside surface of the armature core;* the coils do not thread through the inside of the armature as they do in the ring winding. The drum winding *does not contain as much inactive wire,* therefore, as the ring winding, also the operation of winding the armature, is much more easily accomplished with the drum than with the ring type. These are two of the advantages which make the drum winding so universally used. A typical drum wound armature is shown in Fig. 39. This illustrates a medium sized drum

one-half this number will be the proper number of ampere-turns per coil.

The **B–H** curves given on p. 18 are to be used in this calculation. These curves are plotted between *flux density* and *ampere-turns per cm. length* of the magnetic circuit. Suppose that a ring of cast iron is to be magnetized to a flux density of 5000 lines per sq.cm. and that the average length of the magnetic path in the ring is 75 cm. How many ampere-turns will be required?

By reference to the magnetization curve for cast iron it is seen that to produce a flux density of 5000 lines per sq.cm. 9 ampere-turns are required *per cm. of length of the path.* As the length of the path is 75 cm. the number of ampere-turns required is $75 \times 9 = 675$ ampere-turns.

*Field Coil Calculation.* This same method may be used for calculating the necessary ampere-turns for the magnetic circuit of the machine shown in Fig. 34.

Suppose the necessary flux through the armature core is 1,600,000 lines. There must be through the poles and yoke more flux than this because of the *leakage lines.* If the leakage factor is taken as 1.25 the flux through the yoke and poles is $1{,}600{,}000 \times 1.25 = 2{,}000{,}000$ lines.

The cross-sectional area of the different parts of the magnetic circuit would be given. The average length of the magnetic path in each part may be estimated. From the flux and cross-section the density in each part is calculated and then from the magnetization curves the ampere-turns per cm. are obtained; this quantity multiplied by the length of path in that part of the circuit gives the required ampere-turns for that part. The sum of the ampere-turns required for each part gives the number required for the complete magnetic circuit and one-half this number are to be put in each field coil.

The number of ampere-turns required for the air gaps cannot be obtained from the curve sheet but is easily calculated as follows;

$$\Phi = \frac{.4\pi NI}{\frac{l}{A\mu}}$$

and for air $\mu = 1.$

Transposing $$\frac{\Phi}{A} = B = .4\pi \frac{NI}{l} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

or $$\frac{NI}{l} = \frac{B}{.4\pi} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

The ampere-turns required per cm. of air gap is therefore equal to the flux density in the air gap divided by $.4\pi$. In calculating the magnetic circuit it is convenient to tabulate the data as shown below:

| Part. | Material. | Average Length in cm. | Area in sq. cm. | Flux. | Flux Density. | Amp.-turns per cm. | Amp.-turns. |
|---|---|---|---|---|---|---|---|
| Yoke.... | Cast iron . | 35 | 350 | 2000000 | 5720 | 12 | 420 |
| Poles.... | Cast steel. | 30 each | 200 | 2000000 | 10000 | 3.8 | 228 |
| Air gap... | Air...... | 0.2 each | 250 | 1600000 | 6400 | 5095 | 2038 |
| Armature. | Laminated iron.... | 25 | 225 | 1600000 | 7120 | 1.5 | 37 |

Total ampere-turns required........................... 2723

Ampere-turns to be used per coil $= \frac{2723}{2} = 1362$

We will next figure the necessary ampere-turns for a small modern bipolar machine with a slotted armature and double yoke. In this yoke the flux from the pole divides, half going one way and half the other. The flux in going through the armature teeth is very dense and although the length of path is small it is better to figure this as a separate part of the magnetic circuit, instead of treating the teeth as part of the armature core.

simply conductors. The wires on the outer side of the coil of a ring winding are inductors, because when the armature rotates these wires move through the magnetic field and an e.m.f. is induced in them. Those wires which are on the inside of the armature core and on the ends are merely conductors.

*Superiority of Multiple Circuit Winding.* One reason why the multiple circuit winding is used so much more than the two circuit winding will appear when we consider the voltage generated by a given number of armature inductors, first when connected so as to give a two path winding and then when they are connected to give a multiple path winding.

Suppose we have a 12-pole generator having 1500 active inductors on the armature altogether. The voltage generated per inductor might be 2 volts. If these inductors were arranged in a wave winding all of them would have to be used in only two paths, so that there would be 750 inductors in series in each path. The voltage generated per path would be 1500 and this would be the voltage of the machine. Now this would be much too high for an ordinary c-c. generator, as the highest voltage ordinarily used in c-c. service is 600, which is the voltage of an ordinary railway system.

Suppose now that the inductors were arranged in a multiple circuit winding; as the machine has 12 poles there would be 12 paths in the winding and therefore the number of inductors in series per path would be 125. The voltage per path, which is the same as the voltage of the generator, would be 250 which would be right for a lighting generator.

A machine of the size we have in mind could not use a fewer number of inductors than 1500 because in that case the inductors would have to be of such large cross-section that they could not be bent readily and therefore the operation of winding the armature would be too difficult. Of course the two windings would have the same capacity

The pole shoe serves to increase the area of the air gap so as to reduce the density in this part of the magnetic circuit. Tabulating our data as before, and using the magnetization curves, we have:

| Part. | Material. | Length in cm. | Area in sq. cm. | Flux. | Flux Density. | Amp.-turns per cm. | Amp.-turns. |
|---|---|---|---|---|---|---|---|
| Armature. | Laminated iron | 15 | 100 | 1200000 | 12000 | 4 | 60 |
| Teeth.... | Laminated iron | 1.2 cm. on each side | 70 | 1200000 | 17150 | 95 | 228 |
| Air gap... | Air...... | 0.25 cm. each | 120 | 1200000 | 10000 | 7975 | 3987 |
| Poles.... | Laminated iron | 10 cm. each | 90 | 1380000 | 15350 | 17 | 340 |
| Yoke.... | Cast steel. | 50 | 60 each | 1380000 | 11500 | 5 | 250 |

Total ampere-turns required..................... 4865

$$\text{Ampere-turns per pole} = \frac{4865}{2} = 2433$$

These two examples will serve to show how the number of field ampere-turns is roughly determined. In an actual design other factors have to be taken into account; the effect of the armature m.m.f. on the field strength has to be considered and the problem is somewhat more complicated than we have indicated.

*Proper Size of Wire.* The size of wire to be used in winding the field coils is now to be determined. Generally, all of the field coils of the machine are connected in series and then to some source of e.m.f. from which the field current is to be taken. The average length of one turn of the field coil is estimated from the known size of the field pole and the assumed depth of the coil. Suppose that the length of one turn close to the field pole was 10 inches and that we assume a winding depth of one inch; the length of

an outside turn would be in the neighborhood of 18 inches (if the pole were of rectangular cross-section) so that the *average length* of a turn would be 14 inches.

Let $E$ = the voltage of the field current supply;
$NI$ = the total ampere-turns required on the machine $= NI$ per pole $\times$ number of poles;
$l$ = the average length of one turn, in feet;
$r$ = the resistance per foot of the proper sized wire; this is to be determined;
$I$ = the current through the field circuit;
$R$ = the resistance of the field circuit;
$N$ = the total number of turns on all coils in series.

Then,

$$R = Nlr, \quad \ldots \ldots \ldots \quad (21)$$

and

$$I = \frac{E}{R} = \frac{E}{Nlr}, \quad \ldots \ldots \ldots \quad (22)$$

multiplying both sides by $N$

$$NI = \frac{NE}{Nlr} = \frac{E}{lr},$$

or

$$r = \frac{E}{lNI}. \quad \ldots \ldots \ldots \quad (24)$$

Now $NI$ has been calculated, $E$ is known, and $l$ has been approximately determined from the assumed size of the field coil. Therefore, $r$, the resistance per foot, of the proper sized wire to use, is determined. From the wire table the diameter of the wire and its cross-sectional area in circular mils can be obtained.

Knowing the proper sized wire and the number of red ampere-turns, the proper number of turns is now

to be determined. Here we at once notice a peculiarity in the problem. *So far as the magnetizing effect of the coil is concerned, with a given supply voltage, it makes no difference how many turns are used for the field coil; no matter how many turns are used the m.m.f. of the coil will be the same.*

Suppose that we put on 1000 turns and that this number of turns has a resistance of 50 ohms. If the voltage of the field current supply is 100 volts the field current will be 2 amperes and the ampere-turns of the coil will be 2000. If, now, 2000 turns are used the resistance of the coil increases to 100 ohms, the field current decreases to one ampere and the ampere-turns in the coil will be 2000 as before.

*Proper Number of Turns.* There must be some method of determining the proper number of turns to use; *and this is fixed by the safe allowable temperature rise in the coil.* It is apparent that if, for example, only one turn were used in the field coil, the proper number of ampere-turns would be obtained but the current through the one turn would be so great that the wire would melt. As the number of turns is increased, the required current decreases; when the number of turns has been increased to such an extent that the current which flows through the coil does not heat the wire more than 50° C. above room temperature (the limit fixed by the A.I.E.E.), we may say that the field coil has been properly designed.

The process of predicting the temperature rise from the power used up as heat in the coil ($I^2R$ loss in the coil) and the calculated radiating surface requires judgment and experience, because some radiating surfaces are more effective than others, etc.

It has been found, however, from the results of many tests that a safe figure to use in fixing the number of turns is obtained by allowing 1200 *circular mils per ampere* in the winding. The proper sized wire has already been found and so the cross-section in circular mils is known. Suppose

elementary outline and analysis of some of the various forms employed in different c-c. generators. By the term "armature winding" is meant the group of conductors placed on the armature core, which revolve with it and cut the magnetic field. The different ways in which these conductors may be placed on the armature core and interconnected, leads to innumerable winding schemes. The armatures of motors and generators are wound in exactly the same way; the same factors have to be kept in mind no matter whether the armature is to be used for one purpose or the other. We shall speak of the different windings as generator windings but they serve just as well for a motor armature.

*Classification of Armature Windings.* The armature windings for alternating current generators are quite different from those intended for a c-c. generator; we shall consider here only the c-c. windings, the first two general divisions of which are the **ring winding** and the **drum winding.**

*Ring Winding.* In the ring winding the coils are wound around the armature in such a way that half of the coil is on the *inside of the armature core.* This may be seen by reference to Fig. 38, which shows the armature of an early type of generator. The winding of these armatures is not as easy as the winding of a drum armature but a more important objection is the amount of "dead wire" on the armature.

*Disadvantage of the Ring Winding.* The conductors on the inside of the core do not cut any flux as the armature revolves and hence they can generate no e.m.f. This extra wire is detrimental to the machine not only because of the extra cost for wire but because the *resistance of the armature winding is much larger* than it should be; this high resistance means high $I^2R$ and a high heat loss in the generator. As a result the efficiency is lowered.

The ring winding is used very little at present and we

hence the heat generated in the ribbon can readily escape to the air. In Fig. 36 is shown a view of a wire wound

FIG. 36.—Wire-wound Field Coil. General Electric Co.

field coil and Fig. 37 shows a ribbon wound field coil; the ribbon has been allowed to uncoil partially so that the method of winding may be apparent.

FIG. 37.—Ribbon-wound Field Coil. General Electric Co.

**18. Armature Windings.** The question of armature windings is a very broad one and we can give here only an

elementary outline and analysis of some of the various forms employed in different c-c. generators. By the term "armature winding" is meant the group of conductors placed on the armature core, which revolve with it and cut the magnetic field. The different ways in which these conductors may be placed on the armature core and interconnected, leads to innumerable winding schemes. The armatures of motors and generators are wound in exactly the same way; the same factors have to be kept in mind no matter whether the armature is to be used for one purpose or the other. We shall speak of the different windings as generator windings but they serve just as well for a motor armature.

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The ring winding is used very little at present and we

shall not discuss it further except in connection with the Thomson-Houston arc generator which illustrates another type of winding.

The drum winding is not easy to show by a diagram however and so we shall, in analyzing the action of a drum winding, often picture the drum winding as a ring winding. The ring winding is easier to represent and the deductions we make regarding its action apply equally well to the drum winding.

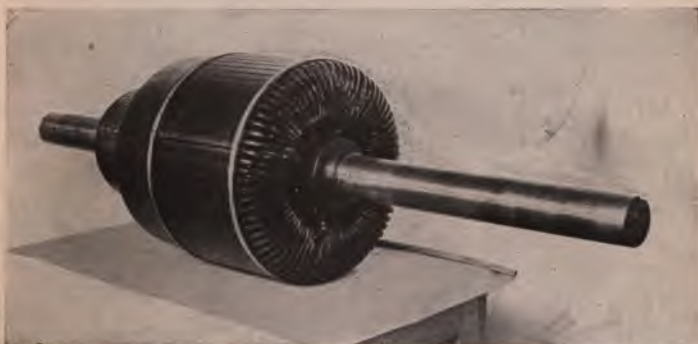

FIG. 38.—View of a Ring-wound Armature (Early Type). Crocker-Wheeler Co.

*Drum Winding.* The drum winding is distinguished by the fact that all of the armature conductors *are on the outside surface of the armature core;* the coils do not thread through the inside of the armature as they do in the ring winding. The drum winding *does not contain as much inactive wire,* therefore, as the ring winding, also the operation of winding the armature, is much more easily accomplished with the drum than with the ring type. These are two of the advantages which make the drum winding so universally used. A typical drum wound armature is shown in Fig. 39. This illustrates a medium sized drum

one-half this number will be the proper number of ampere-turns per coil.

The **B–H** curves given on p. 18 are to be used in this calculation. These curves are plotted between *flux density* and *ampere-turns per cm. length* of the magnetic circuit. Suppose that a ring of cast iron is to be magnetized to a flux density of 5000 lines per sq.cm. and that the average length of the magnetic path in the ring is 75 cm. How many ampere-turns will be required?

By reference to the magnetization curve for cast iron it is seen that to produce a flux density of 5000 lines per sq.cm. 9 ampere-turns are required *per cm. of length of the path.* As the length of the path is 75 cm. the number of ampere-turns required is $75 \times 9 = 675$ ampere-turns.

*Field Coil Calculation.* This same method may be used for calculating the necessary ampere-turns for the magnetic circuit of the machine shown in Fig. 34.

Suppose the necessary flux through the armature core is 1,600,000 lines. There must be through the poles and yoke more flux than this because of the *leakage lines.* If the leakage factor is taken as 1.25 the flux through the yoke and poles is $1,600,000 \times 1.25 = 2,000,000$ lines.

The cross-sectional area of the different parts of the magnetic circuit would be given. The average length of the magnetic path in each part may be estimated. From the flux and cross-section the density in each part is calculated and then from the magnetization curves the ampere-turns per cm. are obtained; this quantity multiplied by the length of path in that part of the circuit gives the required ampere-turns for that part. The sum of the ampere-turns required for each part gives the number required for the complete magnetic circuit and one-half this number are to be put in each field coil.

The number of ampere-turns required for the air gaps cannot be obtained from the curve sheet but is easily *calculated as* follows;

$$\Phi = \frac{.4\pi NI}{\frac{l}{A\mu}}$$

and for air $\mu = 1.$

Transposing $$\frac{\Phi}{A} = B = .4\pi \frac{NI}{l} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

or $$\frac{NI}{l} = \frac{B}{.4\pi} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

The ampere-turns required per cm. of air gap is therefore equal to the flux density in the air gap divided by $.4\pi$. In calculating the magnetic circuit it is convenient to tabulate the data as shown below:

| Part. | Material. | Average Length in cm. | Area in sq. cm. | Flux. | Flux Density. | Amp.-turns per cm. | Amp.-turns. |
|---|---|---|---|---|---|---|---|
| Yoke.... | Cast iron . | 35 | 350 | 2000000 | 5720 | 12 | 420 |
| Poles.... | Cast steel. | 30 each | 200 | 2000000 | 10000 | 3.8 | 228 |
| Air gap... | Air...... | 0.2 each | 250 | 1600000 | 6400 | 5095 | 2038 |
| Armature. | Laminated iron.... | 25 | 225 | 1600000 | 7120 | 1.5 | 37 |

Total ampere-turns required.......................... 2723

Ampere-turns to be used per coil $= \dfrac{2723}{2} = 1362$

We will next figure the necessary ampere-turns for a small modern bipolar machine with a slotted armature and double yoke. In this yoke the flux from the pole divides, half going one way and half the other. The flux in going through the armature teeth is very dense and although the length of path is small it is better to figure this as a separate part of the magnetic circuit, instead of treating the teeth as part of the armature core.

*Insulation of Armature Windings.* After the wire coil is taken from the wooden form, it is taped tightly with insulating tape, the ends are cut to the proper length for connecting to the commutator and are properly bent so that when placed on the armature the front pitch will be

FIG. 48.—Typical Coils Used for a Wave Winding. Note the form of the front connections, as contrasted to those of the coils shown in Fig. 47. Allis-Chalmers Co.

the desired amount. The amount of insulation put on these formed coils before they are ready for use on the armature depends upon the voltage for which the winding is designed. In a high voltage machine several layers of cotton tape and oiled cambric are bound tightly around the coil and

FIG. 49.—Showing an Impregnating Tank (on the right) and Various Armature and Field Coils before and after Impregnation. Crocker-Wheeler Co.

then the coil is impregnated, by the vacuum process, with some good insulating compound.

Fig. 49 shows several sets of such coils after they have been taken from the impregnating tank· some impregnated

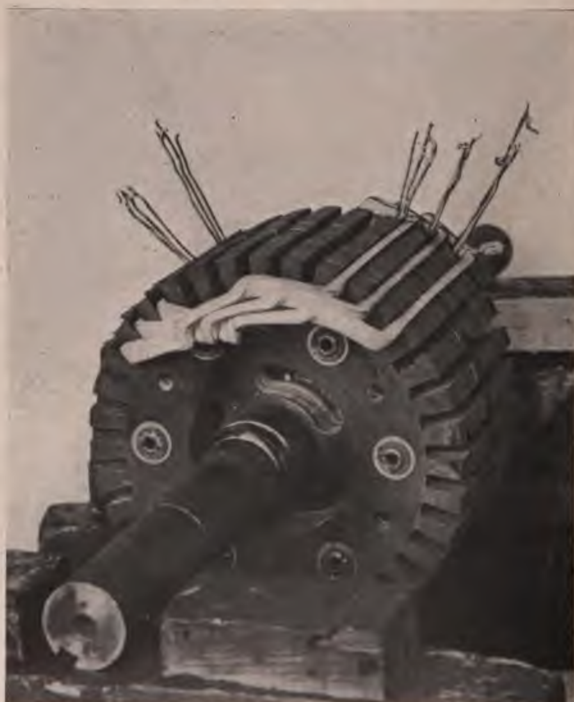

FIG. 50.—Small Armature Partially Wound with Formed Coils. Fish board insulation placed in slots before coil is pushed in. Crocker-Wheeler Co.

field coils may be seen also. Fig. 50 shows an armature core which is partially wound with these formed coils. In Fig. 50 can also be seen the method of preparing the slots before the coil is forced into place. A sheet of tough paper (fiber or fish-board) is bent into the form of a

trough and pushed into the slot and the formed coil is pushed and hammered down into the slot inside this paper trough. This insulating trough extends beyond the ends of the armature core so that as the formed coil is hammered into place there may be no risk of sharp edges on the iron core cutting through the insulation of the coil and so *grounding it* on the armature core.

*Shape of Conductor.* In small machines the armature conductor is generally a round wire, which can easily be

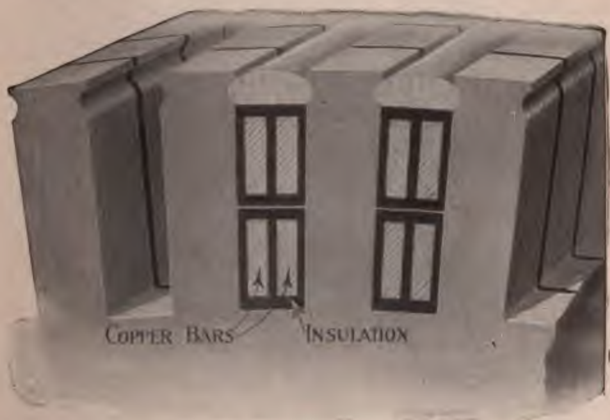


FIG. 51.—Insulation in Slot of a Bar-wound Armature. Allis-Chalmers Co.

bent and shaped in sizes up to about No. 4. B. & S. If it is necessary to use larger cross-section than No. 4, several smaller wires may be used in parallel. When the cross-section necessary is larger than that of a No. 4 wire, a specially shaped conductor would probably be used. A round wire does not use the space in a slot very economically and so a rectangular shaped conductor is generally used on large machines. Fig. 51 shows a cross-section through the slot of a high voltage machine showing how such copper bars fit into a slot, with the insulation around

them, and a wooden wedge fitting tightly into grooves in the sides of the slot near the top, which serves to hold the winding in place and prevent it throwing out as the armature revolves. On small machines no wooden wedge is used; after the coil sides have been hammered snugly into place, a strip of stiff, insulating material is slipped into the top of the slot and then binding wires are wound around the armature periphery. Several bands

FIG. 52.—Showing Binding Wires, Around a Completed Armature. Ventilating ducts may be seen also. Crocker-Wheeler Co.

of such binding wire are generally used, as shown by Fig. 52, which represents the armature of a small c-c. generator.

As the coils are being placed on the armature each end is made fast to its proper commutator bar and, when all the coils have been put in the slots, the end connections are hammered snugly into their proper places. They are then soldered to the commutator bars and the armature is completed.

# CHAPTER III

## THE CONTINUOUS CURRENT GENERATOR

**19. E.M.F. of a C–C. Generator.** In calculating the voltage generated by any machine we start from the fundamental rule that **if a conductor cuts a magnetic field at the rate of $10^8$ lines per second it generates one volt of e.m.f.** Therefore, to find the e.m.f. generated by any machine

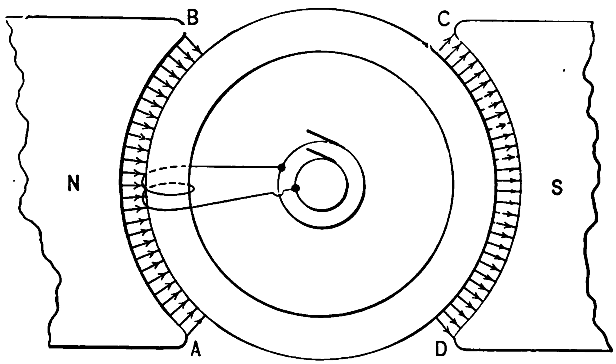


FIG. 53.—Possible Field Distribution in the Air Gap.

it is only necessary to calculate how much flux the armature winding cuts per second. First, a single coil armature will be considered and then the more complicated windings will be taken up.

*E.M.F. form for an Elementary Generator.* Suppose a ring-wound armature with only one coil, the two ends of the coil being connected to two slip rings, as in Fig. 53. These rings are represented one inside the other; really they would

be of the same size and would be placed side by side on the armature shaft. As the coil moves from $A$ to $B$ it is cutting the magnetic field and, as the field is supposed to be of uniform density under the pole face, the e.m.f. generated will be constant during this time. In moving from $B$ to $C$ *no flux is cut*, hence no e.m.f. is generated. From $C$ to $D$ the coil is again cutting flux, but now the e.m.f. will be *in the opposite direction* as compared to the e.m.f. when the coil was moving from $A$ to $B$, because the flux is in the same direction as it was before, but the motion is in the opposite direction. Then, as the coil moves from $D$ to $A$, no e.m.f. is generated.

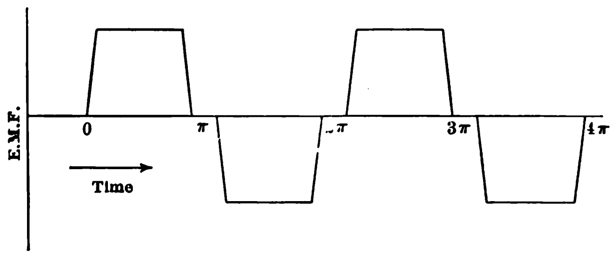


FIG. 54.—E.M.F. Wave Form, Without Commutator.

If the *e.m.f. wave* be represented by using the position of the coil for the $X$ axis and the magnitude of the generated e.m.f. for the $Y$ axis, a curve will be obtained, such as is shown in Fig. 54. Calling the position zero when the coil is at $A$, it is evident that when the coil has revolved 180° the negative part of the e.m.f. begins; and, of course, when the coil has rotated 360° (i.e., back to $A$) the cycle of events begins over again.

Such a machine gives, then, an e.m.f. which alternates in direction once every time the coil moves by a pole and, if an external circuit were connected to the brushes ($a$) and ($b$), an alternating current of the same shape as the e.m.f. wave of Fig. 54, would flow in it.

*Action of Commutator.* To make the simple machine of Fig. 53 give a current which, *in the external circuit, is uni-directional,* it is necessary to connect the ends of the coil to the two segments of a two-part commutator and

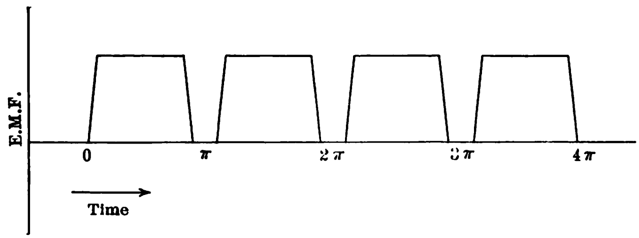


Fig. 55.—E.M.F. Wave Form, With Commutator.

to so place the brushes on the commutator (diametrically opposite to one another) that, *at the same time that the e.m.f. of the coil reverses the connection of the coil to the external circuit reverses.* When this is done a pulsating, uni-direc-

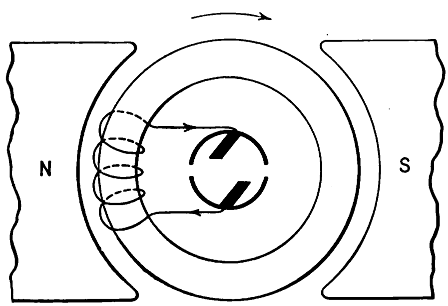


Fig. 56.—Connections and Brush Position for One-coil Armature.

tional current as shown in Fig. 55 flows in the external circuit.

The commutator and proper position of the brushes to give such a current in the external circuit are shown in Fig. 56, where the brushes are shown inside the commu-

tator for clearness of representation. They really bear on the outside surface of the commutator.

A single coil does not form a closed winding and would never be used. If another coil is wound on the armature in the same direction as the first, and if the coils are connected as in Fig. 57, we have a two-coil, closed circuit winding. The direction of the induced *e.m.f.* is marked on both coils by arrows and it is seen that the e.m.f. of both coils acts in the same direction *as far as the outside circuit is concerned,* but that the two e.m.fs. oppose one another n the local circuit made up of the two coils only. In this

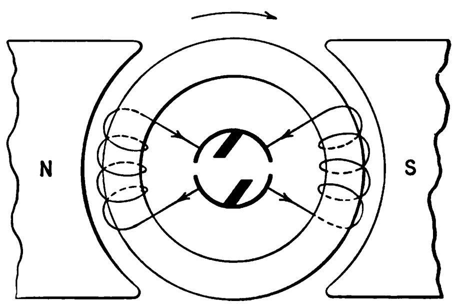


FIG. 57.—Two-coil Armature and two-part Commutator.

two-circuit winding *the e.m.f. of the generator is evidently the same as the e.m.f. per path, but the current capacity of the machine is equal to twice the current capacity per path.* The e.m.f. wave form of the armature shown in Fig. 57 would be exactly the same as that shown in Fig. 55, which was for a single coil armature.

*Necessity of Many Coils.* The e.m.f. wave of Fig. 55 is not suited for ordinary purposes of lighting, running motors, etc. A uniform, non-pulsating e.m.f. is desired and this is the purpose of making an armature with many coils and many commutator bars. Consider a four-coil, closed circuit armature with a four-part commutator,

connected as shown in Fig. 58. As the armature revolves it is evident that every coil will generate a wave of e.m.f. of the same shape and magnitude as that of any other coil but that these waves will be behind one another, a time equal to that required for one-quarter of a revolution of the armature. Moreover the e.m.f. of the machine is obtained at any time by adding together the e.m.fs. of the two coils that are in series with each other at that time in the path considered.

*E.M.F. Form of a Four-coil Armature.* The e.m.fs. of the different coils are shown in Fig. 56 (*a*) the curves

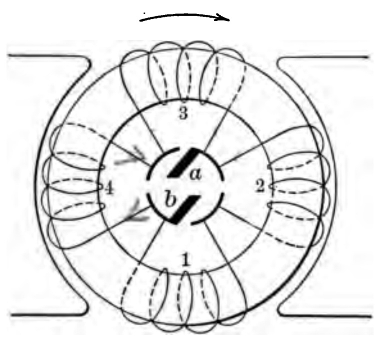


FIG. 58.—Four-coil Armature and Four-part Commutator.

being numbered to correspond with the coils. Thus at time = 0 coil No. 1 is just moving under the $N$ pole and beginning to generate an e.m.f. While it is still generating voltage, coil No. 2 moves under the same $N$ pole and also generates an e.m.f. in the same direction as that of coil No. 1. Then between the brushes these two coils are acting in series and the line e.m.f. is the sum of these two.

The e.m.f. generated by the other half of the armature winding is obtained by considering coils No. 3 and No. 4. It will be found that they give, between the brushes, an e.m.f. exactly equal to that given by coils No. 1 and No. 2

and in the *same direction with respect to the external circuit.* The line e.m.f., obtained by adding the coil e.m.fs., is shown by the broken line of Fig. 59 (*b*). It is seen that although the line e.m.f. is not yet regular, it never goes to zero value as with the one coil winding (Fig. 55) and that the fluctuation is only 50% of the maximum value.

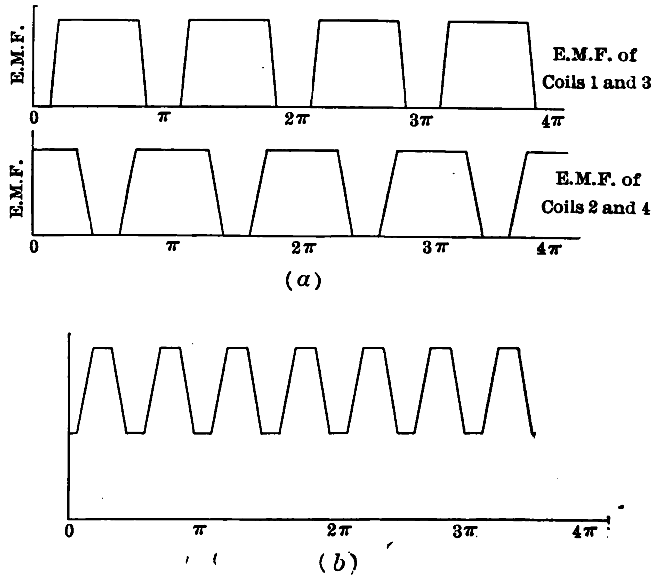


FIG. 59.—Wave Forms for Four-coil Armature.

*E.M.F. Variation in an Ordinary Generator.* By considering in the same way an 8-coil armature with an eight-part commutator it will be found that, as the number of coils is increased, the pulsation in the line e.m.f. continually decreases, and, on an ordinary commercial machine having perhaps 20 coils between brushes, the variation is scarcely perceptible and can only be detected by some sensitive instrument like the telephone. Besides getting smaller in magnitude as the number of coils is increased the fluctua-

tions of e.m.f. also increase in rapidity until on commercial generators they are in the neighborhood of 1000 or more per second.

We see, then, that *a multiple-coil armature, equipped with a multiple-part commutator, will produce a uni-directional line e.m.f. of practically constant magnitude;* the machine is therefore called a **continuous current** or **direct-current generator.** The e.m.f. in the individual coils is alternating in direction; the commutator cannot change this, but it does so change the connection of the coil to the line that what is, in the coil, an alternating e.m.f. becomes uni-directional on the line.

*Method for Calculating the E.M.F. of a Generator.* In determining the e.m.f. of a generator it is only necessary to calculate at what rate flux is being cut by all the conductors connected in series in one path of the winding. We shall use the term **active inductors** to indicate those conductors on the armature which are cutting flux at the time considered. Evidently all the inductors on an armature are not active because while some of them lie under the pole face, generating an e.m.f., others must be situated in the interpolar space where there is no flux to be cut and hence they can generate no e.m.f. Generally 60% to 70% of the inductors of a machine are active.

Also we have to consider the fact that some of the active inductors lie in a weaker field than others. The field may be considered in two parts; that directly under the pole face where the field has normal density, and that near the edge of the pole or pole shoe, where the density of the field is less than normal. This part of the field is called the **pole fringe.** To calculate the e.m.f. of the machine it is necessary to find the voltage generated, (*a*) by inductors under the pole face and, (*b*) by inductors in the pole fringe, and then add the two voltages so obtained.

*Example of E.M.F. Calculation.* We will first consider a bipolar machine wound with 44 coils of 8 turns each of

No. 13 wire. The total length per turn is 2 feet, of which 1 foot is active. Assume the peripheral speed of the armature to be 3000 feet per minute, that 60% of the inductors are active (i.e., lie under the pole face at the same time), and that the flux density in the air gap is 10,000 lines per sq.cm., the pole fringe not considered. It is desired to find: (1) the generated e.m.f.; (2) the safe current capacity; (3) the armature resistance; (4) the full load terminal voltage.

The first thing to determine is the *active length of inductor per path.* This must be a two path winding, hence we have:

Coils per path $=22$;

Turns per path $=176$;

Length of inductor per path $=176\times 1=176$ ft.;

As the flux density is given in lines per sq.cm. we will work in the metric system;

Length of inductor per path $=5370$ cm;

Active length of inductor per path

$$=5370\times 60\%=3220 \text{ cm};$$

The velocity of the inductors is 3000 ft. per minute

$$=1525 \text{ cm. per sec.};$$

Flux density $=10000$ lines per sq.cm;

Flux cut per second $=3220\times 1525\times 10000$

$$=491\times 10^8 \text{ lines.}$$

Hence the generated voltage per path $=491$ volts, and this is the generated e.m.f. of the machine.

*Allowable Current.* In a well ventilated armature it is safe to allow one ampere per 600 circular mils cross-section of the armature conductor. As a No. 13 wire is 5178 cir. mils in section the safe current to allow is about 8.63 amperes per path. As there are two paths in parallel

in this armature, and as each can safely carry 8.63 amperes, the armature can carry about 17.3 amperes. If we had supposed a poorly ventilated armature and allowed 900 circular mils per ampere, the safe current would have been 11.6 amperes.

*Calculation of Armature Resistance.* The resistance of the armature is obtained by calculating the resistance per path and then dividing by the number of paths in parallel in the armature. In the machine above there are in each path 22 coils of 8 turns each and each turn is 2 feet long. The length of wire per path is therefore 352 feet. The resistance of 352 feet of No. 13 wire (at 50° C.) = 0.786 ohms. As there are two paths, the armature resistance is $\frac{0.786}{2}$ or 0.393 ohms.

*Calculation of Terminal Voltage.* The full load $IR$ drop in the windings is therefore

$$0.393 \times 17.3 = 6.8 \text{ volts (say 7 volts).}$$

The drop at the brush contacts (carbon brushes assumed) = 2 volts. Therefore

the total drop in the armature with full load current = 7 + 2 = 9 volts.

The full-load terminal voltage (voltage at brushes) = 491 volts (generated) − 9 volts ($IR$ drop) = 482 volts.

*Another Problem.* Next consider a 12-pole, lap-wound generator having 240 coils on the armature, 4 turns per coil each turn consisting of two No. 8 wires in parallel. The length per turn is 4 feet and the length of inductor per turn is 20 inches. The armature is 4 feet in diameter and makes 200 r.p.m. 50% of the inductors lie in a field of 9000

No. 13 wire. The total length per tu
1 foot is active. Assume the peripher
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sq.cm., the pole fringe not considered.
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voltage.

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*per path*. This must be a two path win

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Turns per path $=176$;

Length of inductor per path $=176\times 1=$

As the flux density is given in lines per
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Length of inductor per path $=5370$ cm;

Active length of inductor per path
$=5370\times 60$

The velocity of the inductors is 3000 f
$=1525$ cm.

Flux density $=10000$ lin

Flux cut per second $=3220\times 15$
$=491\times 10^{8}$

Hence the generated voltage per p
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*Calculation of Armature Resistance.* ...
the armature is obtained by ...
path and then dividing by the number of ...
in the armature. In the machine ...
path 22 coils of 8 turns each ...
The length of wire per path is ...
resistance of 352 feet of No. ...

As there are two paths the ...

0.193 ohms.

*Calculation of Terminal Voltage.* ...
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lines per sq.cm. and 20% of them lie in the pole fringe where the average flux density is 5000 lines per sq.cm. Find the same quantities as in previous problem.

To calculate the generated e.m.f. the method of precedure is to find: (1) the length of inductor in the denser field and calculate the e.m.f. generated by it (*A*); (2) the length of inductor in the weak field and calculate the e.m.f. generated by it (*B*). The sum of (*A*) and (*B*) gives the total generated voltage.

As the machine is lap wound and is 12 pole, there must be 20 coils per path.

The length of inductor per path

$$=20\times4\times20\times2.54=4070 \text{ cm.};$$

The length of inductor in the dense field

$$=4070\times50\%=2035 \text{ cm. } (A);$$

The length of inductor in the pole fringe

$$=4070\times20\%=814 \text{ c.m } (B);$$

$$\text{The peripheral speed}=\frac{4\times200\times2.54\times12}{60}=1275 \text{ cm./sec.}$$

E.m.f. generated by inductors (*A*)

$$=1275\times2035\times9000\times10^{-8}=233 \text{ volts}$$

E.m.f. generated by inductors (*B*)

$$=1275\times814\times5000\times10^{-8} = 52 \text{ volts}$$

Total e.m.f. per path $=285$ volts

The conductor of which the winding is formed is a double No. 8 and so has a cross-section of 33,020 circular mils.

Allowing 600 circular mils per ampere gives a capacity per path of 55 amperes. As there are 12 paths in parallel and each can carry 55 amperes the whole armature has a

capacity of $12 \times 55 = 660$ amperes. The length per turn is 4 feet, therefore the length per coil is 16 feet. There are 20 coils in series in one path, therefore the length per path = 320 ft.

The resistance of 320 ft. of No. 8 wire is (at 50° C.) 0.224 ohm.

The resistance of 320 ft. of double No. 8 is therefore 0.112 ohm.

Hence the armature resistance is $0.112/12 = .00934$ ohm;

$$\text{Full load } IR \text{ drop} = 660 \times .00934 = 6.16 \text{ volts.}$$

Allowing 2 volts for the drop at the brush contacts gives a full load $IR$ drop in the armature of about 8 volts, so that the full load terminal voltage $= 285 - 8 = 277$ volts.

In these two sample problems the data was not taken from actual machines. The voltages obtained are not those of commercial machines. Certain voltages have been more or less standardized, by usage, for certain classes of service. The voltages ordinarily used are 125 and 250 volts for lighting generators, and for railway generators 550–600 volts. Very special machines may be built for voltages as high as 10,000 volts, but these are seldom used. Generators intended for electroplating are generally built for 10 volts or less.

**20. Field Excitation.** The field coils of a dynamo-electric machine may be supplied with current from the armature of the machine itself in which case it is called a **self-excited machine,** or the power for the field coils may be furnished from some other electric circuit, in which case the machine is said to be **separately excited.** In general we may say that all c-c. machines use self-excitation while practically all alternating current generators have to be separately excited.

The field current of any generator, whether c-c. or a-c., must be continuous; the poles must be continuously excited in the same direction. Now the e.m.f. of an a-c.

generator alternates in direction so that evidently the field current of such a machine could not come from its armature. A small c-c. generator, called an **exciter,** is usually employed to furnish the field current of an a-c. generator.

*Different Field Windings.* As was pointed out in the last chapter the required number of ampere-turns may be supplied by using a large number of turns and a small current, or a few turns with a large current. The field winding may be connected in parallel with the armature of the machine; the coils are then wound with many turns of comparatively fine wire, possibly as large as No. 14 on large machines while small machines might be wound with No. 20 or smaller. When the field of a c-c. generator is so connected across the armature terminals, i.e., in shunt, or parallel, with the external circuit the machine is said to have *shunt-excitation,* and the winding is called a **shunt field.**

When but a few turns of heavy wire are put in the field coils, the field winding is connected *in series* with the external circuit and the field is called a **series field.**

In most c-c. generators the field coil is wound in two parts. The larger part of the coil is made up of comparatively small wire and forms the shunt field, and the smaller part of the coil is wound of a few turns of large wire or copper ribbon and forms a series winding for the generator. Such a generator, having the two kinds of field coils, is said to be **compound wound.**

Diagrams of the three kinds of windings are shown in Fig. 60; (*a*) being the shunt, (*b*) the series, and (*c*) the compound winding. In the compound winding the shunt field may be connected directly across the armature as in the full lines of Fig. 60 (*c*) or it may be connected across the armature and series field both as shown in the dotted lines in the same figure. The first connection is called a *short shunt* while the second (the one in dotted lines) is *called a long shunt.* A coil for a compound wound gen-

erator is shown in Fig. 61. It is seen that the coil is made in two parts. The outside coil of few turns is the series field; it is noticed that the terminals which lead the current

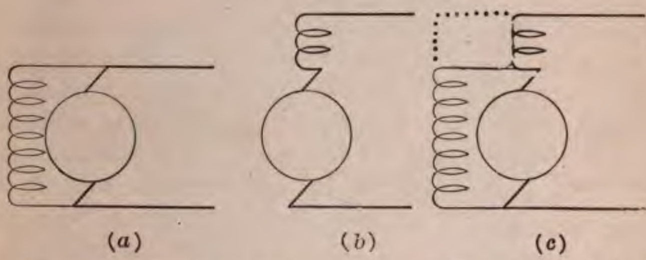


FIG. 60.—Various Field-circuit Connections; *a*, Shunt Field; *b*, Series Field; *c*, Compound Field. In *c* the short shunt connection in dotted lines.

in and out of this coil are heavily constructed so as to carry safely a large current. The current through a series coil may be several hundred amperes on a large machine.

FIG. 61.—View of a Field Coil for a Compound Generator. Westinghouse Elec. and Mfg. Co.

*Field Rheostats.* In series with the shunt field of any generator is generally placed a variable resistance (see Fig. 62), made of some high resistance material imbedded in enamel, porcelain, or other heat resisting body. The amount

of resistance can be varied by a movable shoe (carried on an arm that rotates) which makes contact with any one of many taps on the resistance. This adjustable resistance is called a **field rheostat.** A diagram of the connections of the movable contact and the taps of the resistance is shown in Fig. 63. Figs. 64 and 65 show the external appearance of the rheostat, the connections of which are given in Fig. 63. The cast-iron plate serves as a mechanical support for the enamel and resistance wire, and also serves to radiate the heat generated in the resistance wire.

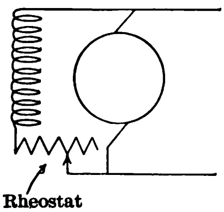



FIG. 62.—Connection of Field Rheostat.

*Tapering a Rheostat.* The size of wire used in a field rheostat is "tapered;" the wire is much larger on one end than on the other. If a rheostat is connected in series with a shunt field (as in Fig. 62) and the amount of resistance in the rheostat is varied evidently the cur-

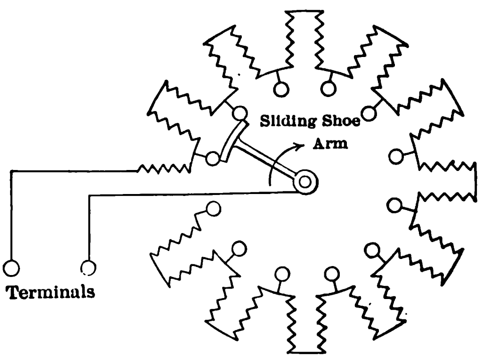



FIG. 63.—Inside Connections of a Field Rheostat.

rent through the rheostat and field winding will vary. As the rheostat is "cut out" (i.e., as its resistance is lowered) the current in the circuit increases; for this

reason the rheostat wire is made larger on the first steps than on the last steps. The amount of taper is generally


FIG. 64.—Front View of a Field Rheostat. Ward Leonard Co.

FIG. 65.—Back View of a Field Rheostat. Ward Leonard Co.

2:1, i.e., the rheostat can safely carry twice as much current on one end as on the other.

*Rating a Rheostat.* A certain field rheostat might be rated on its name plate: Resistance 35 ohms, maximum current 8 amperes, minimum current 4 amperes. This rating signifies that the total resistance of the rheostat is 35 ohms, that it will safely carry 4 amperes *through all of its resistance* and that the *first step* will safely carry 8 amperes. Such a rheostat would be suitable for a field having 28 ohms resistance connected to a 220-volt source of supply. When the rheostat was "all in," the current would be somewhat less than 4 amperes and when only the last step of the rheostat was connected in the circuit the current would be about 8 amperes.

*Relation of Rheostat to Field Resistance.* If this rheostat was used to regulate the field of a small generator (say one having 200 ohms resistance in the shunt field) it would not have much effect. The change in field circuit resistance from the "all in" position of the rheostat to the "all out" position would be from 235 to 200 ohms and quite probably this amount of change would not be sufficient. The field rheostat to be used with any generator must be properly designed for the field circuit of that generator. A rheostat suitable for one field will not be at all suitable for another.

*Shunting the Series Field.* It is impossible to design the series field of a compound generator with exactly the right number of turns; these field coils are therefore always "over-designed." By this is meant that the coil is wound with more turns than are really necessary to give the required number of series field ampere-turns, when all of the generator output current is flowing through them.

The action of this series field is weakened by putting *a shunt* across the terminals of the series field. This shunt, generally made of German silver, ribbon-shaped conductor, serves as a by-pass for part of the load current. The division of the load current between the series field and the series field shunt depends upon their relative resistances. *adjusting the* resistance of the shunt the number of

ampere-turns in the series field (for any given load) may be changed as desired. After this shunt has once been adjusted it is not necessary to change it, and so it is not made adjustable; in this respect, it is different from the shunt-field rheostat.

**21. Commutation.** The function of the commutator and its construction have been taken up in previous paragraphs, and mention has been made of the fact that there may be sparking at the contact surface of the brush and commutator. The reasons for this sparking will now be given, the superiority of the carbon brush over the copper brush will be shown, and the purpose of the commutating poles will be discussed.

The direction of the current through any coil is reversed as the commutator bars, to which the coil ends are attached, move under the brush. This must be so because before the coil reaches the brush as at ($A$) Fig. 66 the current is in one direction and when the coil is at ($B$) the current is in the opposite direction in the coil. This reversal of current takes place just as the coil is short-circuited by the brush ($C$) Fig. 66. The reversing of the direction of current in the coil as the coil moves under the brush is called **commutation.** If this reversal takes place with no visible sparking at the brush contact, the machine is said to have sparkless commutation.

*Effect of Self-induction on Commutation.* The time in which this reversal of current has to take place is very short so that *the rate of change of current* as the coil is commutated is very high, especially when the machine is carrying much load. As the coil possesses self-induction this rapid reversal of current sets up an e.m.f. of self-induction which tends to maintain the current in its original direction. When this e.m.f. of self-induction is high it is almost impossible to obtain sparkless commutation and because of this fact armature coils must be made with low self-induction. The low coefficient of self-induction is obtained by winding

but few turns per coil and by placing the coil in an open or semi-closed slot. An armature wound in closed slots would not commutate well at all because of the high self-induction of its coils.

*Rate of Current Change During Commutation.* The time during which the coil is short circuited is easily calculated. Suppose a commutator having 90 segments is making 1800 r.p.m. and that the brush has a width equal to two commutator bars. Any two adjacent bars have a coil connected between them so that the coil is

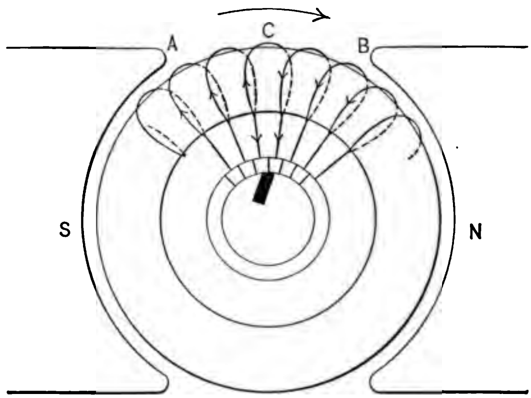



FIG. 66.—*C* Represents Position of Coil being Commutated.

short circuited during the time required for the mica insulation between the two bars to move the width of the brush contact.

In the above case this is equal to $2/90 \times 60/1800 = 1/1350$ of a second. If the armature is carrying 10 amperes per path the rate of change of the current during commutation is about 27000 amperes/sec. The e.m.f. of self-induction is equal to the coefficient of self-induction for the coil, $L$, multiplied by the rate of change of current, and as this latter term is so high, L must necessarily be kept

low. For a given brush width and commutator speed the rate of current change during commutation increases directly with the current the armature is carrying. This rate is very large on big machines and therefore the coefficient of self-induction must be kept correspondingly low. It will be noticed that on large armatures the coils have very few turns; sometimes only one turn per coil is used.

*Methods for Getting Sparkless Commutation.* As the coil moves under the brush the *variation of the contact resistance* between the brush and the two segments to which the coil is attached tends to make the current in the coil reverse. In low voltage, slow-speed machines this effect is great enough to produce sparkless commutation and it is unnecessary to introduce into the short circuited coil an e.m.f. to overcome that of self-induction. Commutation which depends only upon this resistance effect to eliminate sparking is sometimes called **resistance commutation.** If some means is employed to generate in the short circuited coil an e.m.f. equal and opposite to that of self-induction, the machine is said to have **e.m.f. commutation.** Of course, even if a machine employs e.m.f. commutation, the resistance effect is also present, helping the e.m.f. effect.

*Resistance Commutation.* The idea of resistance commutation may be understood by studying the variation of the contact resistance as the commutator bars move under a brush. Consider only a few-coils of the armature shown in Fig. 66; the coil undergoing commutation and a few on each side of it are shown in Fig. 67, where $B$ is the coil about to be commutated. Actually the coil $B$ moves and the brush is stationary; in the diagram we have shown the brush as moving backward on the commutator and the coil as stationary because it is easier to represent the relative motion of the two in this way. The brush marked (1) gives the first position of the brush, that marked (2) the second position we wish to consider, etc.

Position (1) shows coil $B$ before it begins to be com-

mutated, when all the current flowing through the left side of the armature has to go through coil $B$ and lead $c$ to reach the brush and so the external circuit. When the brush is in position 2, this current has *two paths* by which to reach the external circuit; through coil $B$ and lead $c$ as before or else not through coil $B$ at all but directly through the lead $b$. The division of the current between these two paths depends upon their relative resistances and *practically all the resistance of either path is in the brush contact.* Now as the brush moves from position (2) to

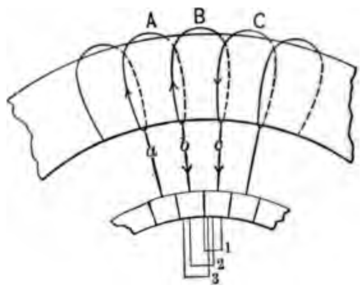



FIG. 67.—Backward Motion of Brush Corresponds to Forward Motion of Armature.

position (3) it is seen that the brush contact area diminishes for one path and increases for the other. The original path through coil $B$ and lead $c$ contains the brush contact whose area is continually diminishing. *But if the area is diminishing the resistance is increasing in this path;* at the same time the resistance of the second path (directly through lead $b$ and not through coil $B$) is decreasing. Therefore, during the time the coil is short circuited this variation of brush contact resistance tends to stop the flow of current through coil $B$.

We shall now see how the current is started through *in the other direction* by the same effect.

Fig. 68 shows the developed winding and commutator and also indicates the position of the field poles. Three positions of the brush are shown corresponding to three positions of the armature; the brush is shown as moving backward, having position No. 1 at an earlier time than position 2, etc. In position 1 the current from the right-hand part of the winding gets to the outside circuit through lead *d* and segment *g*. In position 2 this current has two paths of about the same resistance through *d* and *g* as before or through coil *B* lead *b* and segment *f*. Whatever

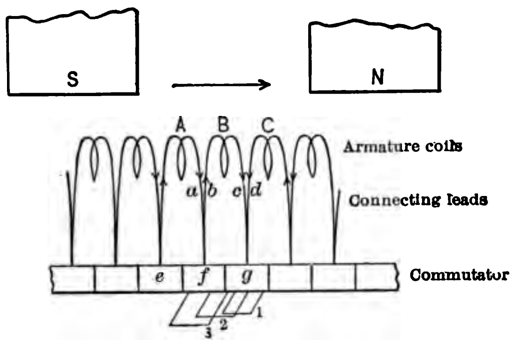



**Fig. 68.—Showing Possible Paths for Currents from Coils to Brush.**

current does take this latter path will evidently oppose the current which has previously been flowing in *B*. So that the actual current through *B* may be considered as the difference between the current coming from *A* and that coming from *C*.

With the brush in position 3 it is seen that the resistance of the path through segment *g* is very high, as the area of brush contact on this segment is very small. Hence in this position most of the current from the right side of the armature winding comes through leads *d* and *c*, through coil *B*, and then through *b* and *f* to the brush. Hence we see that *at the same time* that the variation of

*brush contact resistance is tending to stop the original current through B it is tending to build up an equal current in the opposite direction.*

*Current During Commutation.* If this resistance commutation is to work successfully the current through *B* must have reversed and built up to the same value of current as that flowing in coil *C, before segment g leaves the brush.* If this condition is not satisfied, there will be more or less sparking. The variation of current in coil *B*, as

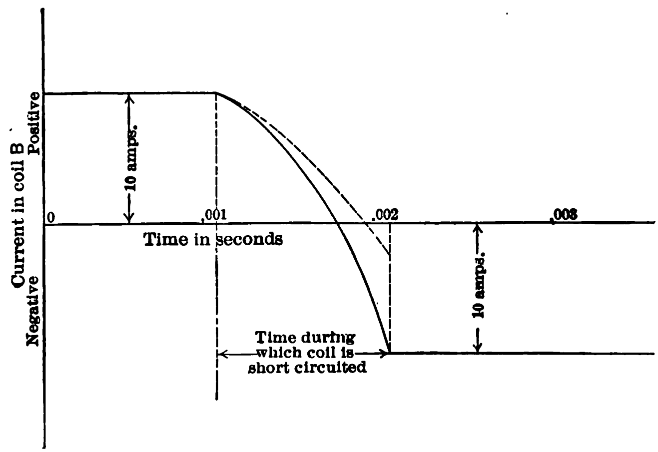



FIG. 69.—Possible Variation of Current During Commutation.

it is being commutated, may be well shown by a curve, as in Fig. 69. If the current is 10 amperes in each side of the armature and the time during which the coil is short circuited is .001 second, and if the current in *B* completely reverses during this time, the current curve has the form shown by the full lines in Fig. 69.

Now suppose that the effect of varying the brush contact resistance is not great enough to reverse completely *the current in B* during .001 second. The current curve

then might have the form shown by the dotted curve of Fig. 69. In this case at the time when segment $g$ leaves the brush the current $B$ is only 2 amperes (negative); it should be 10 amperes (negative). But if the current flowing in the right-hand part of the armature cannot reach the external circuit through segment $g$ *it must go through coil* $B$, and this means that at the instant the brush and segment $g$ separate the current in $B$ must suddenly change from 2 amperes to 10 amperes. The rate of change of current in $B$ is very large at this instant and so a large counter e.m.f. of self-induction is set up in $B$.

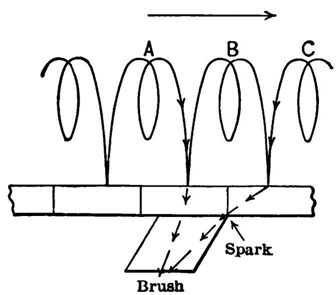



FIG. 70.—Place where Spark Appears.

*Cause of Sparking.* The current from $C$ has then two possible paths; it may force its way through $B$ against the high counter e.m.f. of $B$ or it may form an arc over the mica insulation and get to the brush without going through coil $B$. This condition is indicated in Fig. 70. The formation of this small arc depends upon the high counter e.m.f. of coil $B$ and this in turn depends upon the rapid change in current through $B$ when segment $g$ leaves the brush. This rapid change of current is necessary because during the time of short circuit the resistance variation has not been sufficient to reverse completely the current in $B$ (dotted line, Fig. 69).

*Condition for Sparkless Commutation.* If the current in $B$ was completely reversed during the short circuit interval (as in the full line of Fig. 69) there would be no change of current in $B$, as segment $g$ left the brush and hence no counter e.m.f. of self-induction to overcome. In this case there would be no tendency of the current from $C$ to arc over the commutator, as segment $g$ left the brush and there would be no sparking. In fact, *commutation is always sparkless when the current in the coil undergoing commutation is completely reversed during the time the coil is short circuited by the brush.*

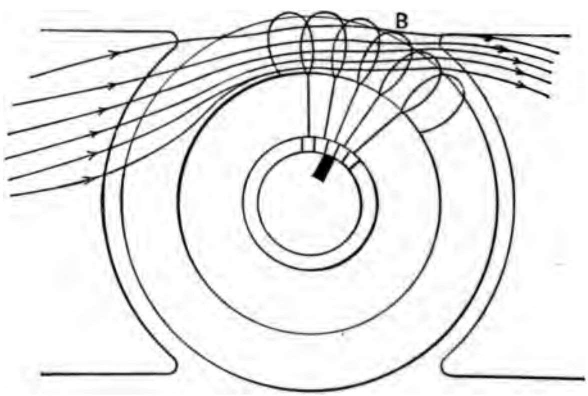



Fig. 71.—Use of Pole Fringe for e.m.f. Commutation.

*E.M.F. Commutation.* E.m.f. commutation is used on nearly all modern machines. With high commutator speeds the resistance variation is never sufficient to reverse completely the current in the coil short circuited, so an e.m.f. is induced in the coil while it is short circuited in such a direction that it assists the current to reverse. This *e.m.f. may* be induced by the pole fringe or by separate

poles intended especially for this purpose called **commutating poles.** If the pole fringe is employed *the brushes are advanced* on the commutator so that the short circuited coil lies in the edge of the magnetic field under the leading pole tips, as shown in Fig. 71. (In case the machine is a motor and not a generator this *brush shift must be backward,* not forward, as in Fig. 71.)

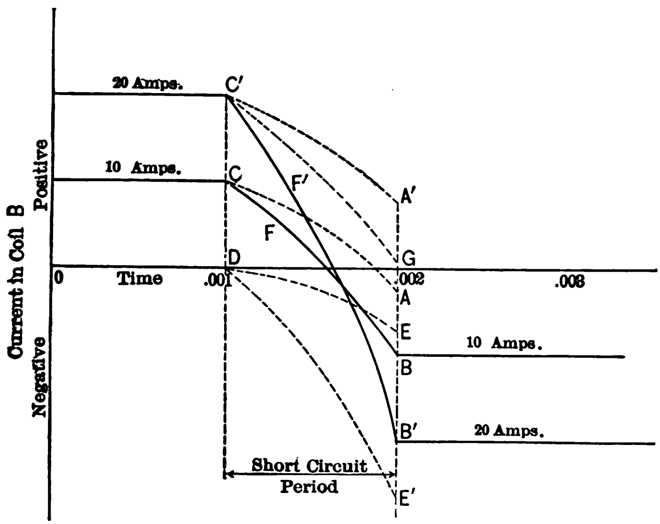



FIG. 72.—Current During Commutation as Load is Changed.

*Current Form in Short-circuited Coil.* The current in the coil during short circuit will now be the resultant of the decaying current, shown in Fig. 69, and the current produced in the short-circuited coil by the e.m.f. induced in it by the pole fringe. It is supposed that resistance commutation is not sufficient and that the current in *B* at the end of the short-circuit period is shown by *A*, Fig. 72, whereas it should be at *B*. The current produced in the short-circuited coil by the induced e.mf. is shown by the

line $DE$ and the total current in the short-circuit coil is the sum of the currents $CA$ and $DE$, shown by $CFB$. This is evidently the current required for sparkless commutation.

If the load on the machine changes so that the current per path is 20 amperes instead of 10 amperes, the e.m.f. required for sparkless commutation is much greater than before. If the short-circuited coil still lies in the same field strength as before, the current in $B$ during short circuit follows the curve $C'G$. The resistance variation, as explained above, gives the current $C'A'$ and the addition of the short-circuit current, $DE$ (the same as before because the e.m.f. producing it is the same) gives the current $C'G$. At the end of the short-circuit period the current in coil $B$ should be at $B'$ (negative), and it really is at $G$ (positive).

*Necessity of Shifting the Brushes with Load Variation.* If the brush is advanced more, so that coil $B$ is in a denser field than before, a greater e.m.f. is induced in it while it is short circuited and the short-circuit current becomes $DE'$. Now $DE'$ added to $C'A'$ gives the current $C'F'B'$, which is just right for sparkless commutation. Hence by means of *brush shifting,* sparkless commutation may be obtained but the amount of shift required varies with the load so that if brush shifting is used the operator has to change the position of the brushes (by moving the brush-holder yoke) as the load changes. The amount of brush shift necessary depends upon the design of the machine. A modern well-designed machine operates fairly well with no brush shift at all. The brushes are placed somewhere between the proper no load position and proper full load position and are left there no matter what the load may be.

*Use of Commutating Poles.* When commutating poles are used, brush shifting is unnecessary. Small poles, wound with a *series winding,* are placed midway between the main poles and the flux produced by them acts in the same way as does the pole fringe just discussed. The *brushes short* circuit the coils lying directly under the

commutating pole and are left fixed in this position; the brushes on a commutating pole machine must never be shifted after correct adjustment has once been made.

As these poles are equipped with a series winding (shown in Fig. 73) the *strength of field produced by them* (and hence the magnitude of the e.m.f. induced in the short circuited coil) is proportional to the load; the magnitude of the short circuit current will then be proportional to the load and it

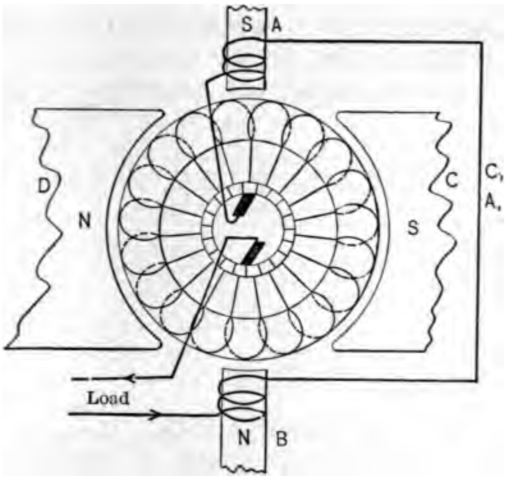



FIG. 73.—Position and Connection of Commutating Poles.

was shown in the discussion of Fig. 72 that this was the necessary condition for maintaining "black" commutation as the load varies. The use of commutating poles (sometimes called **interpoles**) has become almost universal on c-c. motors and generators, especially on **variable speed motors** in which the speed variation is obtained by field weakening. Without the use of commutating poles the variable speed motors could not be built to operate satisfactorily.

The field frame of a machine equipped with commutating poles is shown in Fig. 13. The armature has been

removed to permit a clear view of the field construction. The commutating poles are made very narrow; generally they reach over only two teeth (and the included slot) of the armature core.

**22. Armature Reaction.** When the armature of a dynamo electric machine is carrying current, the armature acts like an electro-magnet and tends to distort the magnetic field produced by the field coils. This action of the armature windings is called **armature reaction.** This action may be a distorting one only, in which case the magnetic field of the machine is not directly strengthened or weakened by the armature reaction, but is merely twisted

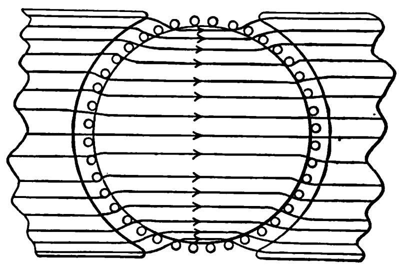


FIG. 74.—Magnetic Field Produced by Field Coils Alone.

out of its normal path. In other cases the armature m.m.f. may not only distort the main field but may either magnetize (strengthen) it or demagnetize (weaken) it.

*Armature Reaction Components.* The distorting action is called the **cross magnetizing action** of the armature and that component of the armature's m.m.f. which directly strengthens or weakens the main field is called its **magnetizing** or **demagnetizing action,** as the case may be. This effect of the armature windings is shown by figures 74, 75 and 76. Fig. 74 shows the field produced by the main field coils, called the **main field;** Fig. 75 shows the field produced by the armature windings when they are carry-

ing current. In this figure a minus sign in the conductor cross-section signifies that the current is away from the observer, and those conductors with a plus sign are carrying current toward the observer. The main field is supposed absent in this figure.

That the armature winding does give a field as shown in Fig. 75 may be seen by supposing conductors 1 and 2 to form one turn of a solenoid; conductors 40 and 3 to form another turn, etc. Thus, each conductor may be imagined as connected with one on the opposite side of the armature and the turns so formed all give an m.m.f. in the direction shown by the field in Fig. 75.

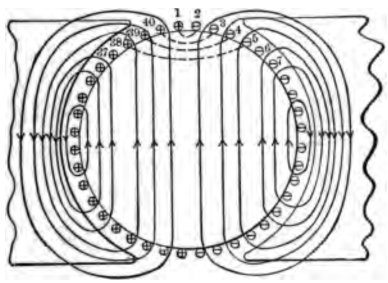



FIG. 75.—Magnetic Field Produced by Armature Coils alone.

*Distortion of Field by Armature M.M.F.* In Fig. 76 is shown the field produced by the resultant m.m.f.; this resultant m.m.f. is obtained by combining vectorially that of the main field with that of the armature. In combining quantities vectorially the quantities are represented by lines drawn from a point in the directions of the quantities and of a length proportional to their value. The diagonal of the parallelogram drawn on these two lines as adjacent sides thus represents the resultant effect of the two.

If the machine is a generator, the main field is twisted *in the direction of rotation of the armature* as shown in Fig.

76; in case the machine is a motor the twist of the main field is in *the opposite direction.* The twist shown in Fig. 76 would be produced by a motor running in the direction opposite to that indicated by the arrow.

*Distortion Proportional to Load.* As this twisting action is produced by the m.m.f. of the armature windings, it must be proportional to the current flowing through the armature, i.e., to the load on the machine. At no load there is no current in the armature windings and hence no armature reaction. The twisting effect is a maximum when the machine is carrying full load or overload.

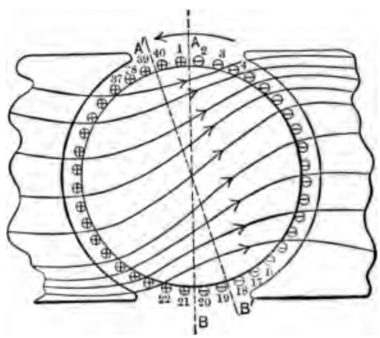



FIG. 76.—Actual Field through Armature is Result of both Field m.m.f. and Armature m.m.f.

*Effect of Distortion on Commutating Plane.* The most important effect of this armature reaction is the shift it produces in the commutating plane. If no armature reaction were present, the coil which is short circuited by the brushes should be in the plane *AB*, Fig. 76 (provided that the necessity of moving the short-circuited coil under the pole fringe for e.m.f. commutation is temporarily neglected). Now the coil in the plane *AB*, Fig. 76, lies in a magnetic field due to the distortion produced by the *armature reaction* and so has an e.m.f. induced in it. This

e.m.f. is, moreover, in the *wrong direction* to produce sparkless commutation. The brushes must therefore, be changed in position from the plane $AB$ to the plane $A'B'$.

*Effect of Brush Shift.* This change in brush position changes somewhat the current distribution in the armature conductors. Some conductors which, before the brush shift, were carrying negative current will now carry positive current, etc. Fig. 77 shows this new distribution of current after the brushes have been moved through the angle $\alpha$; conductors 38, 39, 40, and 1, which, when the

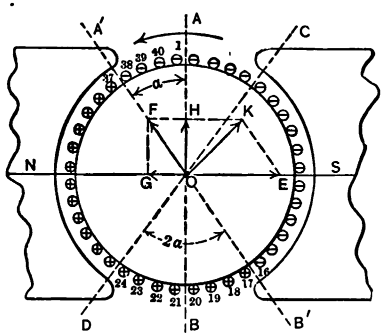



FIG. 77.—Effect of Shifting the Position of the Brushes.

brushes were in plane $AB$, were carrying (+) current, are now carrying (−) current, and conductors 20, 19, 18, 17, which previously were carrying (−) current, now carry (+) current.

*Demagnetizing Turns and Cross-magnetizing Turns.* The armature conductors may now be considered in two groups. Those in the angle $A'OC$, combined with those in the angle $DOB'$, make up a set of turns whose m.m.f. is in direct opposition to that of the main field; these are called the **demagnetizing turns.** Those conductors included in the angle $COB'$, combined with those in the angle $A'OD$, give a m.m.f.

perpendicular to that of the main field; they constitute the **cross-magnetizing turns.**

The field m.m.f. is shown in Fig. 77 by *OE*, the armature m.m.f. by *OF*. The resultant m.m.f. (which actually produces the magnetic field through the armature) is obtained by adding *OE* and *OF* vectorially; it is shown at *OK*. The armature m.m.f. may be divided into its two components, *OH*, the cross-magnetizing force and, *OG*, the demagnetizing force. It is seen that this demagnetizing force is produced

FIG. 78.—Showing Pole Tips with Half as Many Laminations as the Main Part of the Pole.

by all conductors in an angle equal to *twice* that through which the brushes have been shifted.

*Reduction of Field Distortion.* The amount that the main field actually twists under the influence of the armature reaction depends upon how nearly saturated the pole tips are, how long the air gap is and other factors. If, without any distortion at all, the trailing pole tips are saturated, then the field flux cannot crowd any more into these pole tips even if the cross m.m.f. is very large. Laminated pole pieces are generally constructed with the laminations so shaped that only every other one extends

into the pole tips, so that there are in the pole tip only half as many laminations as there are in the pole itself; such a construction is shown in Fig. 78. This construction tends to give saturated pole tips and consequently a field that is not easily distorted; such a field is said to be a "stiff" field.

*Compensation of Armature Reaction.* The magnetizing effect of the armature coils may be neutralized by a **compensating winding.** This consists of a winding imbedded in slots in the pole faces, the winding having one half as many turns as there are turns on the armature. These

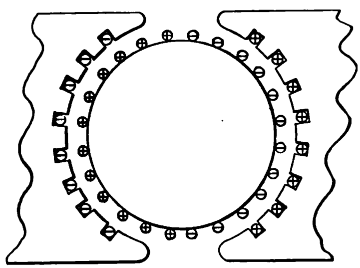


FIG. 79.—Location of a Compensating Winding.

conductors in the pole faces are put in series with the armature so that they carry the same current as the armature, but the connection is so made that every conductor in the compensating winding carries current in the opposite direction to an adjacent conductor on the armature. Fig. 79 shows how these conductors are placed in the pole face and the relative direction of the current in the armature and the compensating winding. The compensating winding is very little used; it makes a machine costly to build and a machine without compensating winding, but equipped with properly designed commutating poles, operates just as well.

*Effect of Armature Reaction on Commutating Poles.* The commutating poles must be designed with turns enough so that the armature cross-m.m.f. is neutralized under the face of the commutating pole and, in addition, the proper amount of flux required for sparkless commutation is forced into the armature core around the coil being commutated. The magnetic circuit of a two-pole generator equipped with commutating poles is shown in Fig. 80. It may be seen that the commutating poles do not prevent the flux from crowding into the tips of the main field poles. But this does practically no harm; the principal thing to

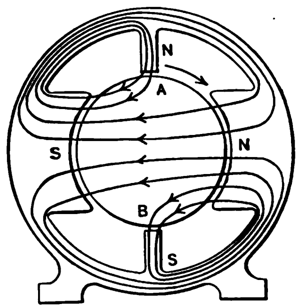



FIG. 80.—Magnetic Flux in a Commutating Pole Machine.

obtain is the proper field for e.m.f. commutation at the two points *A* and *B*.

**23. Characteristic Curves of Generators.** If the load of a generator is increased (speed, etc., being kept constant) the terminal voltage of the generator decreases because of the effects of armature resistance and armature reaction. The curve showing how the terminal voltage changes with increase in load is called the **external characteristic** of the generator. If the terminal voltage is kept constant by increasing the field current (thus increasing the generated e.m.f.) as the load increases and a curve is plotted to show *how the field* current varies with the load, the curve is

called the **armature characteristic** (or field compounding curve) of the generator. Many other curves of similar nature may be constructed and they are all grouped under the general name of **characteristic curves.** By inspection of these curves it may easily be seen how one quantity varies with respect to another, the rest of the variables involved in the operation of the machine being maintained constant.

The most important curves of a generator are the *external characteristic*, the *efficiency*, and the *magnetization curves*. The first two are plotted with terminal volts and efficiency respectively as ordinates and load current as abscissæ in both cases.

**24. Magnetization Curve.** The magnetization curve is plotted between terminal volts and field current, the machine being operated at no load and normal speed while the data for the curve is being obtained. When there is no load on a generator, the terminal volts and generated e.m.f. are the same. The generated e.m.f. is directly proportional to the flux through the armature if the speed is held constant; the curve plotted between no-load terminal volts and field current shows therefore the relation between the field current and the flux which this field current produces, hence its name of magnetization curve.

If the reluctance of the complete magnetic circuit of the machine were constant, no matter how much the flux might be, the magnetization curve would be a straight line. The reluctance of the air gap (which, as shown before, constitutes the principal reluctance of the magnetic circuit) is independent of flux density; the reluctance of the iron part of the path, however, increases as the flux density increases, especially at the higher densities. Hence the magnetization curve of a machine is nearly a straight line but tends to bend over slightly at the higher values of the field current. The amount of bending shows how nearly the iron part of the magnetic circuit is saturated.

In a well designed machine normal voltage is obtained with that value of field current which gives a voltage somewhere near the *knee* of the magnetization curve, as it is called; this point is shown at $C$ in Fig. 81. It is seen that for an increase in field current over the normal field, $OB$, the increase in generated e.m.f. (hence in flux) becomes

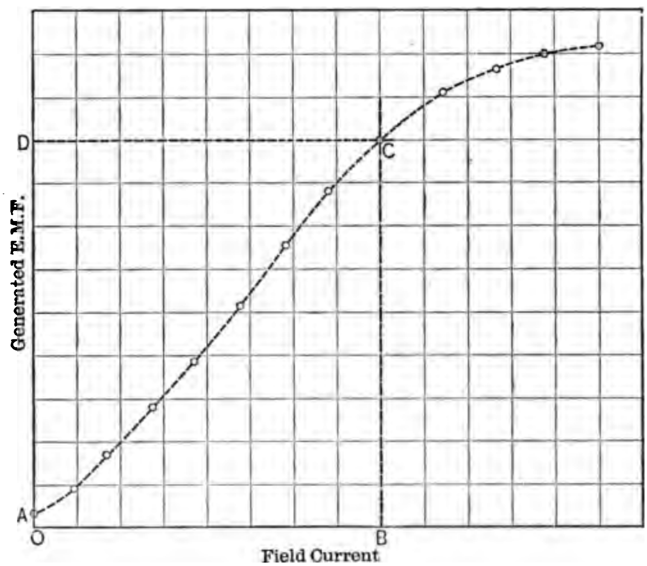



FIG. 81.—Magnetization Curve of a Generator.

smaller and smaller. This condition indicates that the magnetic circuit is becoming saturated.

*Residual Magnetism.* When the field current is zero the generated e.m.f. is not zero but has some small value, perhaps 3% of the normal voltage; this is due to the residual magnetism of the machine. After the field of a generator has once been magnetized the iron pole pieces and yoke stay magnetized to a slight extent and this magnet-*ism which stays* in the frame after the magnetizing current

has been reduced to zero is called the **residual magnetism** of the machine. The amount of this magnetism depends upon the quality of iron used in the magnetic circuit; if all the iron of the magnetic path, poles and yoke as well as armature core was soft and well annealed there would be practically no residual magnetism.

This residual magnetism plays a very important part in the operation of a self-excited generator. When such a machine is starting, there is no voltage developed in its armature, but as the speed increases the residual magnetism gives a small e.m.f. in the armature and *as the shunt field is connected across the armature this small e.m.f. produces a small current through the shunt field of the machine.* This current, even though it is small, increases somewhat the field strength of the machine. As a result the e.m.f. generated in the armature increases and hence more current flows in the shunt field circuit.

"*Building Up.*" This action and reaction between armature and shunt field continues until the generator is operating at normal voltage; it is called the "**building up**" of the generator. It is evident that if there was no residual magnetism in the field this building up operation could not take place; it would be necessary to excite the fields from some outside source every time the generator was started and this would much complicate the operation of a generating station. If a shunt generator, by some chance, loses its residual magnetism (the jarring it receives during shipment might possibly effect such a result) it is necessary to connect its field circuit to some source of electric power and so re-establish the residual magnetism. In doing this precautions must be observed as outlined in Chapter XIV.

The efficiency curve of a generator will not be taken up here as Chapter V will treat this subject in detail.

**25. External Characteristics of Series, Shunt, and Compound Generators.** The terminal voltage of any machine can be obtained for any load by subtracting the armature

*IR* drop from the generated voltage at that same load. The generated voltage at any load is not easy to determine because of the armature reaction effect. In the case of a shunt generator, for example, knowing the value of the shunt field current, we use the *magnetization curve* and so expect to get the true generated e.m.f. for this field current. But the generated e.m.f. with a certain field current and

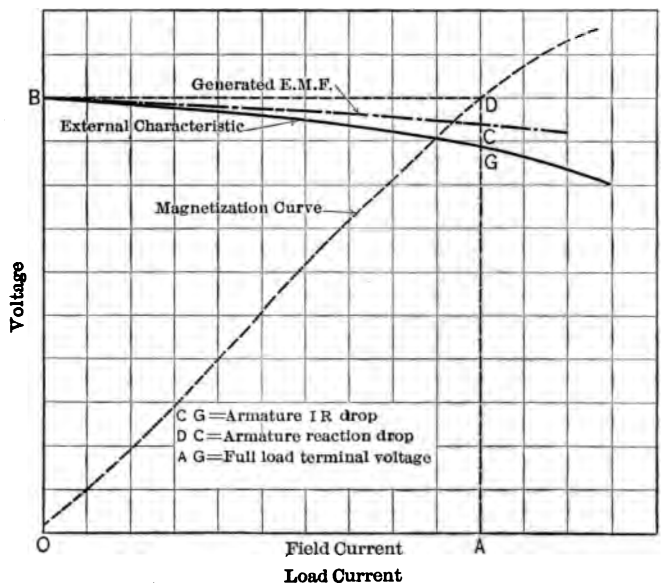



FIG. 82.—External Characteristic of a Separately Excited Generator.

*no load* (under which condition the magnetization curve is obtained) is different from the generated e.m.f. with the same field current when the machine is carrying load. It has been shown that the armature exerts a demagnetizing effect on the main field and thus, even though the field current of a generator is maintained constant, as the machine is loaded the generated voltage falls because of the field weakening due to the armature reaction.

In Fig. 82 are shown the magnetization curve, curve of generated e.m.f. and external characteristic (terminal voltage) of a separately excited generator. The same curves are given for a series generator in Fig. 83, for a shunt generator in Fig. 84, and for a compound generator in Fig. 85. In each case the dotted curve is the magnetization

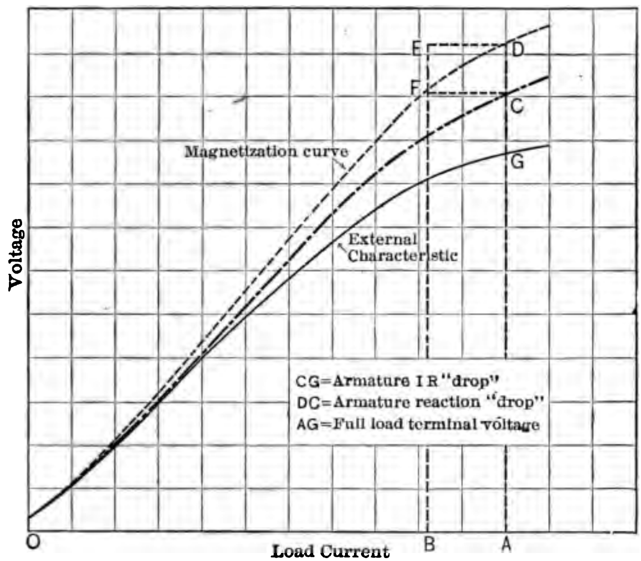



FIG. 83.—External Characteristic of a Series Generator.

curve, the dot-and-dash curve the curve of generated e.m.f. and the solid line curve the terminal voltage.

*Separately Excited Generator.* The separately excited generator has a constant field current as the load changes, but the curve of generated e.m.f. decreases slightly with load increase because of demagnetization by the armature.

*Series Generator.* In the series generator the m.m.f. of the field is directly proportional to the load current and so the generated voltage is nearly proportional to the

load. When the load current is $OA$ we would expect the generated voltage to be equal to $AD$. But the demagnetizing effect of the armature neutralizes part of the field m.m.f. The strength of this armature m.m.f. is taken as equal to $AB$ and hence the *effective* current in the series field is really $OB$ and not $OA$. The current $OB$ gives a voltage on the magnetization curve of $BF$, and $AC$ is equal to $BF$. So $C$ is one point on the curve of generated

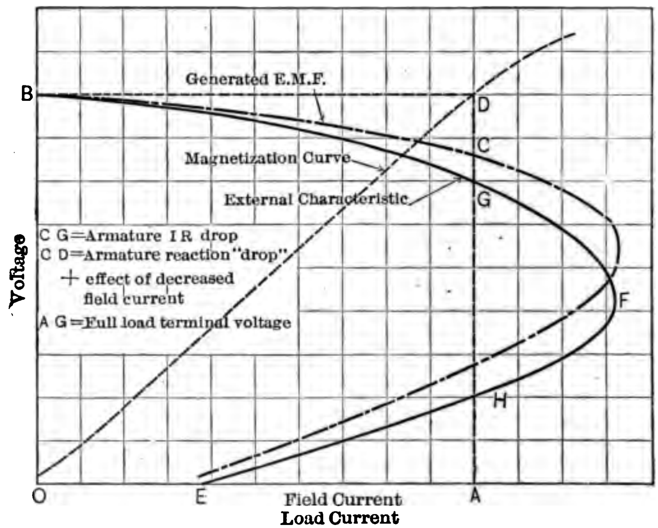



FIG. 84.—External Characteristic of a Shunt Generator.

e.m.f. and other points can be found in similar manner. The armature demagnetizing effect ($AB$) is of course proportional to the load.

*Shunt Generator*. The shunt wound generator has an external characteristic that falls off more rapidly than does that of the separately excited machine because in the shunt generator there are *three effects* tending to make the *terminal voltage* fall as the load is increased. We have

the armature reaction and the armature resistance drop and *in addition, the shunt field current falls as the load is increased because of the lowered terminal voltage.* The shunt field current is evidently proportional to the terminal voltage and so decreases with load increase.

If the resistance of the external circuit of a shunt generator is continually decreased, the external character-

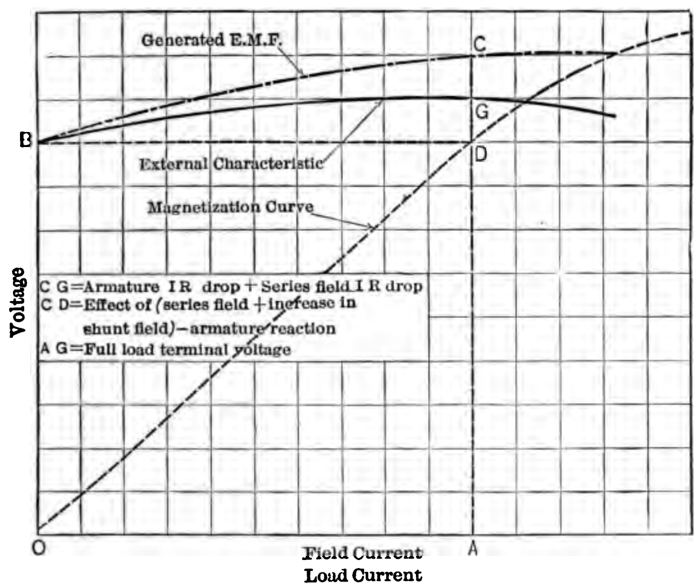



FIG. 85.—External Characteristic of a Compound Generator.

istic doubles back because of the decreased field current. From $B$ to $F$ (Fig. 84) the machine is stable and this is the working part of the external characteristic. The part of the curve from $F$ to $E$ is generally difficult to obtain as the machine does not definitely maintain any special load on that part of the curve.

Even when the terminal voltage is zero ($E$, Fig. 84) there will be some current circulating through the armature.

The field coils can produce no magnetic field because they have no current (the terminal voltage being zero) but there is some residual magnetism to give the armature e.m.f. which produces the short circuit current *OE*. At this point the external circuit has zero resistance and the machine is short circuited.

*Compound Generator*. In the case of the compound generator the curve of generated e.m.f. rises as the load increases. This is due primarily to the fact that the series turns on the field give a magnetizing force which increases directly with the load while the magnetizing effect of the shunt field remains nearly constant; the total magnetizing force, therefore, increases somewhat with the load.

*Amount of Compounding Used*. The amount of increase in generated e.m.f. as the load increases, depends upon the number of turns in the series windings. It is customary to put in the series coils a sufficient number of turns to cause the *terminal voltage of the machine to rise as the load increases;* such a machine is said to be **over-compounded.** The amount of over-compounding is generally about 10%; for example a small lighting generator might be rated as 110 volts no load, 125 volts full load, and a railway generator might be rated as 550 volts no load, 600 volts full load. The amount of over-compounding depends upon the service for which the machine is intended; it may be none at all, in which the machine is said to be **flat compounded.** If there are not enough turns in the series field to keep the terminal voltage from dropping as the load increases, the machine is said to be **under-compounded.** Such machines are never used in practice.

*Use of the Compound Generator*. Practically all machines used in lighting or railway service are over-compounded. In such work the characteristic to be obtained is *a constant voltage at the load,* not at the generator. The life and efficiency of an incandescent lamp are both greatly affected if the voltage of the line to which it is connected goes either

above or below the voltage at which the lamp is rated. Now if the terminal voltage of the generator should remain constant, the voltage of points on the distributing system must fall as the load is increased due to increased *IR* drop in the wires of the distributing system.

In Fig. 86 this point is illustrated. A group of lamps is connected to a center of distribution *B*; the generator is located at *A*. If the voltage at *A* remains constant as the load increases, it is evident that the voltage at *B* must fall because it is always equal to the voltage at *A* minus the drop in the line *AB*. But if the increase in voltage at *A*, from no load to full load, is just equal to the *IR* drop in *AB* when full load current is flowing, then

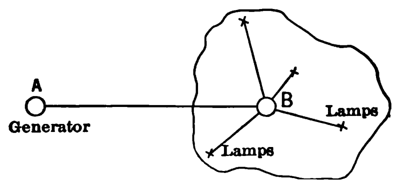



FIG. 86.—Elementary Diagram of a Power Distribution System.

the voltage at *B* will be the same at full load as it is at no load. At intermediate loads the voltage at *B* will be somewhat above normal; the external characteristic of a generator is always more or less curved (due to the variable reluctance of the magnetic circuit) so that if the machine is properly compounded at full load it is always somewhat overcompounded at half load. This effect is not enough to cause any trouble on the system.

Series and shunt wound generators are used but very little in practice. Some special arc light machines employ series excitation but their use is not extensive.

The difference between the no-load terminal voltage and full-load terminal voltage (field excitation and speed constant) expressed in percentage of the full-load voltage is

called the **Regulation** of a generator. Thus a machine having no-load voltage of 121 and full-load voltage of 110 would have a regulation of 10%.

**26. The Three-wire Generator.** A great many electric light installations are equipped with a **three-wire distribution system.** In such a system three wires are used for carrying the current from the generator to the lamps. A diagram of the scheme of connections for such an installation is given in Fig. 87; the voltages given here are those generally used for incandescent lamp circuits.

The generator which supplies such a three-wire system must evidently have three wires connected to it; the extra wire is called the **neutral.** Between each outside wire and

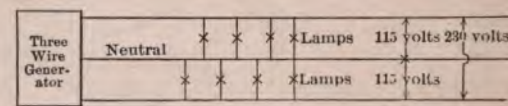



FIG. 87.—A Three-wire Distribution System.

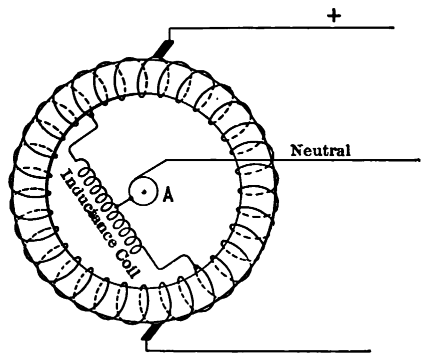
the neutral the lamps are connected so that there is on the lamps an e.m.f. just one-half that between the outside wires.

*Connections for the Third Wire.* The ordinary generator has only two sets of brushes; the special feature in the three-wire generator is the arrangement for connecting the third wire (the neutral) to the armature windings. This is always done by connecting an inductance coil between two diametrical taps on the armature winding and connecting the neutral wire to the center of this coil.

The inductance coil consists merely of several turns of insulated wire wound on a laminated iron core. Sometimes this coil is built right into the armature spider; in other cases it is not in the armature at all but located behind the switchboard.

Fig. 88 illustrates these two schemes. In ($a$) the coil is *mounted in the* armature spider and its center point is

connected to a slip ring, *A*. The neutral wire connects to the brush bearing on this ring. (In Fig. 88 the commutator has been omitted and the two ordinary brushes are shown as making contact on the periphery of the arma-



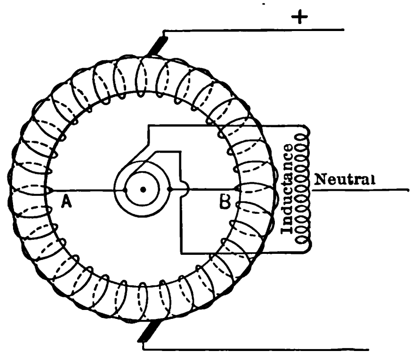




FIG. 88.—Connections for a Three-wire Generator.

ture. This is done merely to keep the diagram clear.) In the scheme shown at (*b*) the two diametrical taps *A* and *B* connect to two slip rings and so through brushes and leads to the outside inductance.

*Current in the Neutral.* When the load on the two sides of the system is exactly balanced the neutral carries no current at all. When the load is unbalanced the neutral wire carries a current equal to the amount by which the load is unbalanced. For example if there is a load of 100 amperes on one side of a three-wire system and only 70 amperes on the other the neutral will carry the difference, 30 amperes.

**27. Capacity of a Dynamo-electric Machine.** The capacity of a generator or motor is limited by either one or the other of two effects, namely, *heating* or *commutation.*

*Features Limiting the Temperature Rise.* As the load on a machine increases, more current must flow through its armature (and series field if the machine has one) and the heat produced in these circuits is proportional to the square of the current. The temperature to which the windings will rise depends upon two factors; the rate at which heat is *produced* and the rate at which it can be *radiated,* or sent off into the surrounding medium. The rate at which heat is radiated from any body (e.g., an armature) depends upon the difference in temperature between it and the surrounding air and upon the amount of air that is carried over the radiating surface. This second condition is really involved in the first because if but little air is supplied it soon gets hot and so reduces the temperature difference whereas if a lot of air is supplied, as in forced ventilation, the air is carried away from the radiating surface before it has time to get hot.

*Effect of Ventilation Upon Capacity.* In Fig. 89 are shown two sets of curves, those for heat radiation and that for heat production. The curve *OAB* gives the rate of heat production plotted against the armature current as abscissæ. The three lines *OC*, *OD*, and *OE*, show the rate of radiation for good, medium and poor ventilation; the abscissæ for these curves are the difference between the armature temperature and room temperature. (It is supposed that the air for ventilation is taken directly

from the room and is therefore at the same temperature as the room.)

The safe temperature rise in ordinary machines has been fixed by the *A.I.E.E.* at 50° C. above room temperature, hence the line *KM* is erected (in Fig. 89) at this value. With good ventilation the rate of radiation at this temperature is equal to the rate of heat production by the current *OG* and so we say the safe current, in so far as heating is concerned, is *OG*. If the ventilation is medium the safe current is *OH* and if the ventilation is poor the

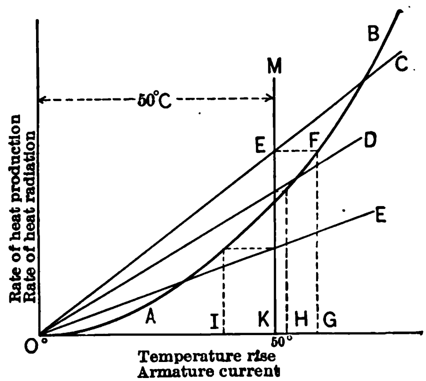



Fig. 89.—Curves of Heat Generation and Heat Radiation.

safe current is *OI*. This diagram shows the enormous advantage of forced ventilation gained by equipping an enclosed machine with a ventilating fan and proper air ducts. By this means it is possible to increase its safe current capacity by 200% or 300%. A certain railway motor for example, might be rated as 75 h.p. with ordinary ventilation and by suitable ventilation *its rating might be increased to perhaps 200 h.p.* Practically all enclosed machines are now designed with the idea of getting the best ventilation possible.

*Commutation Limits Capacity.* The other limit to the

capacity of a machine is fixed by the sparking at the commutator. As was explained in the discussion of commutation, the current in any coil has to reverse during the short interval of time during which it is short circuited by the brush. Now the liability to spark at the commutator was shown to depend upon the *rate of change of current* necessary during the commutating period. As the time during which commutation has to take place is constant (for a given speed), the rate of change of current depends directly upon the load the machine is carrying and so the liability to spark depends directly upon the load. It has been shown, however, how the commutating pole, producing in the short circuited coil an e.m.f. *proportional to the load,* overcomes this difficulty and in commutating pole machines the limit of capacity is set by heating and not by commutator sparking.

*Special Insulation Increases Capacity.* There is of course one other method by which a machine of given size may have its rating much increased and that is by using only insulating materials which will stand higher temperatures. The limit of 50° C above room temperature is proper for such insulating materials as cotton, shellac, oiled cambric, etc. If a machine could be built with nothing but mica and asbestos for insulation, it might run safely at very high temperatures. Asbestos has been used to some extent but it is difficult to work this material into uniform sheets and coverings and, also, it absorbs moisture readily. If some good heat resisting insulator could be discovered the possible output of electric machinery could be much increased.

There is one bad feature connected with this high temperature of operation; the resistance of the windings increase quite rapidly with the temperature and so results in an increased $I^2R$ loss and therefore in a lower efficiency.

**28. Operation of C–C. Generators in Parallel.** A *generating station* has ordinarily several generators, all of

which, or only one of which, may be operated to supply the station output.

*Use of Several Generators Instead of One.* The reasons that several small sized generators are used to supply the station output, instead of one large one, are two in number; reliability and efficiency. Suppose the load on a station is represented in the form of a curve, load in kw. being plotted against time. An average curve would be as shown in Fig. 90; the supposed load being made up of railway traffic, lighting, and power for factories. The peak

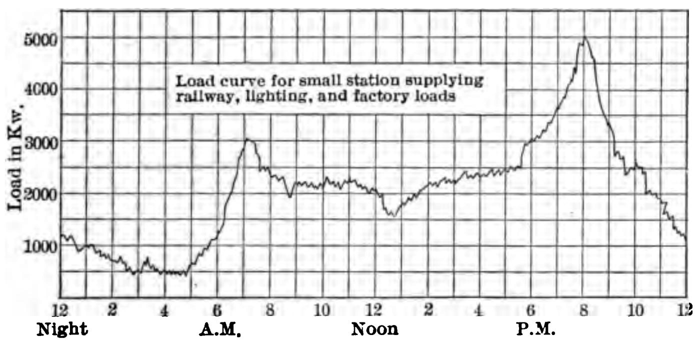



FIG. 90.—A Possible Load Curve for a Small Power Station.

load occurs at 8 o'clock in the evening, and is about 5000 kw. As the peak lasts only a short time, one generator of 4000 kw. rating would fit the needs of the station in so far as quantity of power was concerned. Such a generator would be run overload for a short time but as a machine must be able to carry 25% overload for two hours no harm would result. But there would be two bad features about such a station: 1st, if an accident happens to the machine the station is without power of any sort until the machine is repaired, and 2d, during most of the day the machine would be operating with a load of less than 50% of its

full load rating and consequently the efficiency would be rather low. (See Chapter V).

*Typical Installation.* The proper installation to supply a load curve as given above would consist of two 2500 kw. machines and one 1000 kw. machine. Then from 12 o'clock until 6 o'clock the 1000 kw. machine would be running and the other two would be shut down. During most of the day one 2500 kw. machine would be used and during the two hours of peak load the two 2500 kw. machines would be used, or one 2500 kw. and the one 1000 kw. machine would do because a generator will carry 30% overload for a short time.

In such a station it is to be noticed 1st, that *whatever generators are running are operated at practically full load under which condition the efficiency is a maximum* and 2d, *any two generators of the three which are installed have sufficient capacity to carry the station load.* Therefore continuity of service is guaranteed and the station operates efficiently; of course the first cost of the station would be considerably higher for the three-generator equipment than for the one-generator equipment.

*Parallel Connection of Generators.* In a station only one set of bus-bars is used, no matter how many generators there may be in the station. **Bus-bars** is the name given to the heavy copper bars which run the length of the switch board (behind it) and to which all generators and feeders are connected. The positive bus connects to the positive terminals of all machines in operation and all negative terminals are connected to the negative bus. Such a connection is called a **parallel connection** of generators; all generators send their power into the one set of bus-bars and the load, supplied by various feeders, is taken from them, as shown in Fig. 91.

*Division of Load.* The question naturally arises as to how these generators will divide the total load. Will each *take half* or what will the division be and how is it deter-

mined? We have said that motors and generators are reversable in their action and it may be that under special conditions generator No. 2 may not be a generator at all but may be running as a motor, generator No. 1 supplying the necessary power to do this, besides supplying all of the power required by the load.

In the case of shunt wound generators as shown in Fig.

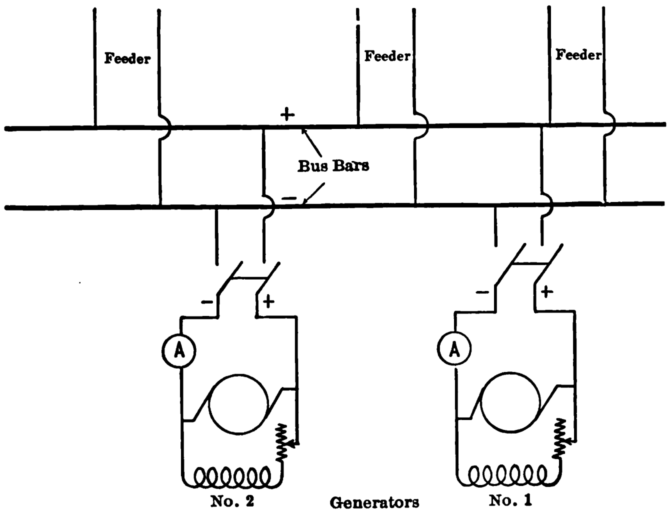



FIG. 91.—Elementary Diagram of Station Connections for Shunt Generators.

91 the division of load is easily regulated and may be shifted from one machine to the other by simply manipulating the field rheostats. If the external characteristics of the two machines are known, the division of load may be determined at once because of the fact that *the terminal voltage of both machines must be the same* as they both connect to the same bus-bars.

Fig. 92 shows the external characteristics of the two

machines; it is supposed that at no load the two machines generate the same e.m.f. This is brought about by variation of one or the other of the field rheostats. Machine No. 2 is supposed to have an external characteristic that drops with load increase more than that of No. 1. When

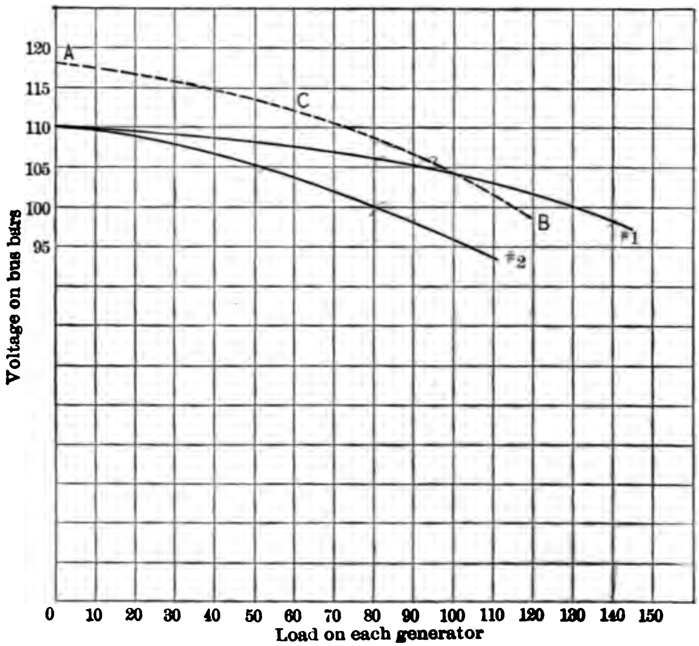



FIG. 92.—Curves to Show Division of Load between Two Shunt Generators in Parallel.

the load is 140 amperes evidently No. 1 must be supplying 90 amperes and No. 2 supplying 50 amperes and the line e.m.f. (i.e., the terminal voltage of the two machines) is 105 volts.

If the load current is increased until the bus-bar voltage *falls to 100 volts* machine No. 1 must be carrying 130

amperes and No. 2 80 amperes and the load is therefore 210 amperes.

*Equalization of Load.* Suppose it is now desired to equalize this load between the two machines, so that each machine carries 100 amperes. This may be done either by increasing the field current of No. 2 (cutting out some of its field rheostat) or by decreasing the voltage of No. 1 (by increasing its field rheostat resistance). Suppose that the voltage of No. 2 is increased by increasing its field current, until its external characteristic crosses that of No. 1 at 100 amperes; the external characteristic of No. 2 is raised throughout the whole range of the curve and is shown by the dotted line *ACB*, in Fig. 92. When the load is 200 amperes, each machine wil ltake one-half of the load but at lighter loads No. 2 will now take more current than No. 1; when the load is 120 amperes for example, No. 2 takes 80 amperes and No. 1 only 40 amperes.

*Generators of Different Capacities.* If the two external characteristics coincided with each other throughout their length and the load was once equally divided, it would be equally divided for all loads. It may be, however, that the two machines are not of the same capacity; No. 1 might have a full load capacity of 100 amperes and No. 2 of only 50 amperes, in which case we would want the division of load to be proportional to the capacities. In this case the two characteristics *must be similar in shape and the no-load and full-load voltage of the two machines must be the same;* if No. 1 gives 110 volts at no load and 105 volts when carrying 100 amperes No. 2 should give 110 volts at no load and 105 volts when carrying 50 amperes. With such external characteristics No. 2 would always carry one-half as much current as No. 1.

*Disconnecting a Generator from the Bus-bars.* If it is desired to disconnect one generator from the bus-bars its load is first reduced to zero by increasing the resistance of its field rheostat until its *generated e.m.f.* is the same as the

bus-bar e.m.f.; when the generated and terminal e.m.fs. of a machine are the same there can be no current flowing through its armature. When the load is zero, the generator switch is opened and then the generator may be stopped. When it is necessary to connect an additional generator to the bus-bars, due to load increase, its terminal voltage is first made equal to the bus-bar voltage then the generator switch is closed; the machine will take no load on closing

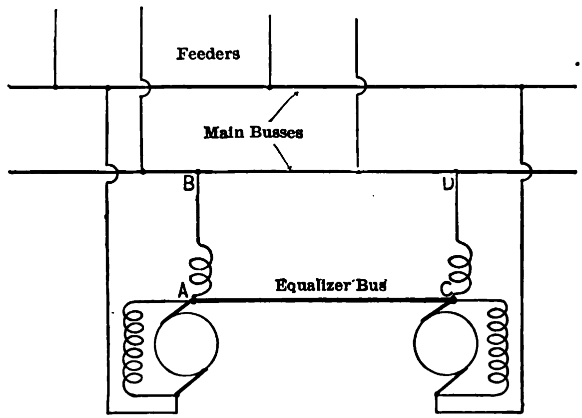



Fig. 93.—Elementary Diagram of Station Connections for Two Compound Generators in Parallel.

the switch but its load may be brought to any derired value by decreasing the resistance of its field circuit.

*Load Division with Compound Generators.* When over-compounded generators are operated in parallel, it is necessary to install an extra bus-bar called the **equalizer bus-bar.** The diagram of two compound generators, connected for parallel operation is shown in Fig. 93.

Without this equalizer bus the parallel operation of two compound generators is unstable; they will not divide the load equally but on the contrary one machine will stop

furnishing load altogether and will operate as a motor from the other generator.

The external characteristics of the two machines are given in Fig. 94 at $AB$ and $AC$. Suppose the load is 130 amperes and that machine No. 1 is supplying 50 amperes and No. 2, 80 amperes, the bus-bar voltage being 115 volts. Now something may happen to change the load on No. 1

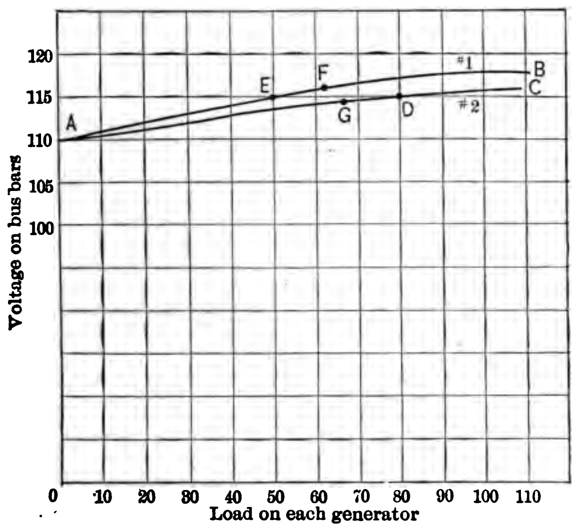



FIG. 94.—Curves to Show Load Division between Two Compound Generators in Parallel.

to 60 amperes and so its voltage rises to the point $F$ on the line $AB$. As the whole load is 130 amperes, machine No. 2 will now carry only 70 amperes and so we should expect machine No. 2 to operate at the point $G$ of its external characteristic. But the terminal voltage of No. 1 is now higher than that of No. 2 and as they are connected to the same bus-bars this is really an impossible condition. Machine No. 1, however, being at higher terminal voltage

than No. 2, will force current through the armature of No. 2 besides furnishing the current to the feeders. The final result is that No. 1 operates at some extreme point on its external characteristic, furnishing all of the 130 amperes for the load and in addition enough to run machine No. 2 as a motor.

If the action had started the other way (i.e., machine No. 1 had for some reason, decreased its share of the load from 50 amperes to 40 amperes) then the decrease in the load of No. 1 would have continued until No. 2 was furnishing all of the load current and enough to run No. 1 as a motor. The operation of two such machines is therefore unstable; any action which starts a re-distribution of the load continues until one machine is carrying all of the load and the other has become a motor.

*Action of the Equalizer Bus.* It will be noticed that this instability is due to the action of the series field; that machine which momentarily increases its load at the same time increases its terminal voltage and the terminal voltage of the other machine must fall as part of its load is taken away by the first machine. Now the function of the equalizer bus is to get rid of this instability and *it does this by maintaining the IR drop over the two series fields equal at all loads.* As the resistance of the equalizer is practically zero, as is that of the main bus-bar, it is evident that the drop in voltage from $A$ to $B$ must be equal to that from $C$ to $D$ (Fig. 93).*

Suppose No. 1 tries to increase its share of the load; the $IR$ drop from $C$ to $D$ must increase and *therefore so must the IR drop from A to B increase.* But the $IR$ drop from $A$ to $B$ can only increase if the current through the

* It will be noticed that the resistance of the cables connecting the machines to the switch board must be treated as part of the series field circuit. Evidently the drop in voltage from $A$ to $B$ (or $C$ to $D$) is equal to the drop in the series field proper plus the drop in the connecting cables.

series field of machine No. 2 increases and if this field current increases the voltage of No. 2 must increase also. Hence any increase in voltage of No. 1 is accompanied by an increase in the voltage of No. 2 and therefore No. 2 will continue to furnish its share of the load.

It was noticed that without the equalizer bus when No. 1 increased its load (and thereby its voltage) the voltage of No. 2 *decreased* and this was the cause of the unstable operation; when the equalizer bus is used, however, if No. 1 increases its load the voltage of No. 2 increases also, thereby causing No. 2 to continue to carry its share of the load.

Another way of looking at the same problem is to notice that the two series fields are put in parallel by the use of the equalizer bus and so any increase in one field must be accompanied by a corresponding increase in the other.

If two compound generators of equal capacity are to operate in parallel and divide the load equally, they must have identical external characteristics and *the resistances of their series field circuits must be equal.* We say series field circuit instead of series field because generally the series field is paralleled by a shunt and it is the resistance of the double circuit, series field with shunt in parallel, which must have the same value for both machines.

*Compound Generators of Different Capacities.* If two compound generators of unequal capacity are to operate well in parallel, dividing the load according to their capacities, the two machines must be adjusted to give the same no load and full load voltages and *the resistances of the two series field circuits must be inversely proportional to their capacities.* This last condition evidently is fulfilled if the full load $IR$ drop is the same for each series field circuit.

# CHAPTER IV

## THE CONTINUOUS CURRENT MOTOR

**29. Relation between Generator and Motor.** As has been said before the c–c. generator and the c–c. motor are nearly identical in construction; the construction which is best for one is generally best for the other; a machine which runs well as a generator will generally operate satisfactorily as a motor.

*Difference in Operation.* Although the construction of the two is practically the same the operation of one machine differs quite materially from that of the other. The generator is always rotated by some prime mover at a speed as nearly constant as possible. The motor, on the other hand, has no prime mover but is supplied with electrical power instead of mechanical power as is the case with the generator. The speed of an electric motor is generally not constant as the load is varied; in some cases this speed variation may be small while in others the highest speed of operation may be several times as great as the lowest speed.

The function of a generator is to generate an e.m.f. by moving conductors through a magnetic field while the prime function of a motor is to produce a turning effort, or **torque.**

*Torque Acting in a Generator.* When a machine is operating as a generator and its armature is carrying current, *it too,* develops a torque (because the armature con-

sists of conductors carrying current, in a magnetic field) and this torque *opposes* the motion of the armature. The current in the armature flows *with* the e.m.f. generated in the moving armature. We may say, therefore, that so far as mechanical power is concerned the generator is *absorbing* energy and so far as electrical power is concerned the machine is *giving out* energy.

*Torque Acting in a Motor.* In the case of a motor the armature turns in the same direction as that in which it is urged by the force acting on the armature conductors; the mechanical power must therefore be positive, or *output*. When the armature revolves it must generate an e.m.f. (conductors moving in a magnetic field generate an e.m.f.) and the current in the motor armature flows in a direction opposite to this e.m.f.; the e.m.f. generated in a motor armature is therefore called a **counter e.m.f.** As the current flows against the armature e.m.f., the electrical power of a motor must be negative, i.e., *input*.

**30. Types of Continuous-current Motors.** The classification of motors is generally made according to the kind of field winding they have. The three types are the **shunt, series, and compound.** In the shunt wound machine the field consists of many turns of fine wire and is connected in parallel with the motor armature. The series motor has a field winding consisting of a few turns of heavy wire connected in series with the armature. The compound motor has two sets of field coils; one of many turns of fine wire in parallel with the armature and another of a few turns of heavy wire in series with the armature.

The series winding of a compound motor may be so connected that it *assists* the shunt winding in magnetizing the field, or it may be so connected that the m.m.fs. of the two windings *oppose* one another. The first is called a **cumulative-compound** motor and the second a **differential-compound** motor; the latter type is of so little use and of so little practical importance that it is seldom met in practice.

The term, compound motor, is therefore used to designate that type in which the series and shunt fields assist one another.

The characteristics of the three types of motors are given here and will be explained more fully in the later paragraphs.

*The shunt motor* has a fair starting torque and nearly constant speed for all loads. It is used where the load requires practically constant speed and the starting torque demanded is not excessive.

*The series motor* operates through a wide range of speed as the load changes, and at very light loads the motor is likely to "run away," i.e., reach dangerous speeds. It gives very great starting torque and is therefore used where a heavy starting torque is demanded and the motor may be positively connected to its load. The principal application of this motor is in railway service.

*The compound motor* has a starting torque greater than that of the shunt motor but less than that of the series motor. It has, however, a definite upper speed limit and if all of its load is removed it will not run at dangerous speeds. Its principal application is in elevator service, machine tool drive, etc., where a fixed speed limit is necessary and considerable starting torque is required. The number of series turns used on the field coils varies somewhat, according to the service required of the motor, but, in general, we may say that, at full load, the series ampere-turns are from 10% to 50% of the shunt ampere-turns. The decrease in speed from no load to full load may vary from 12% to 50% in different motors.

**31. Torque of a Motor.** A motor develops torque because on the periphery of its armature are placed conductors through which current flows and those conductors lying under the pole faces are in a magnetic field. These conductors are then acted upon by a force which tends to *move them* in a direction perpendicular to the magnetic

field and to their length; such a force must then act as a tangential force on the periphery of the armature.

*Force Acting on a Conductor in a Magnetic Field.* The fundamental formula which we shall use in calculating torque gives the relation between the length of the conductor, the strength of the field in which the conductor is lying, the current in the conductor and the force on the conductor. *If a conductor l cms. in length lies in a uniform magnetic field of a density of H lines per sq.cm. (direction of conductor being perpendicular to field) and carries a current of I amperes, then the conductor is acted upon by a force which tends to move it in a direction perpendicular to its length and to the direction of the magnetic field, and the magnitude of this force, in dynes, is given by the equation*

$$f = HlI/10. \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

If we wish to express $H$ in lines per sq.in., $l$ in inches, $I$ in amperes, and $f$ in lbs. we shall have

$$f = 2.54l \times \frac{H}{2.54^2} \times \frac{I}{10} \times \frac{2.205}{981000} = .885HIl \times 10^{-7}. \quad (26)$$

*Illustration of Formula.* Suppose that a conductor 10 inches long lies in a field of 60000 lines per sq.in. and carries a current of 100 amperes. The force on the conductor in lbs. is evidently

$$f = 60000 \times 100 \times 10 \times .885 \times 10^{-7} = 5.31 \text{ lbs.}$$

If we desired the force in dynes we have

$$f = \left(\frac{60000}{2.54^2}\right) \times (10 \times 2.54) \times \frac{100}{10} = 2{,}360{,}000 \text{ dynes.}$$

*Direction of Torque the Same for all the Armature Conductors.* In Fig. 96 is sketched the section of a four-pole motor. The conductors marked (+) are carrying current

away from the observer and those marked (−) are carrying current toward the observer. The conductors under pole *A* carry current away from observer and the flux is directed downward, therefore they will all exert a force toward the left as indicated by the arrow under them. Those under pole *C* carry current in the same direction as those under *A* but the direction of the field is upward therefore the force is toward the right as shown by the arrow under pole *C*. The conductors under the two poles *B* and *D* give

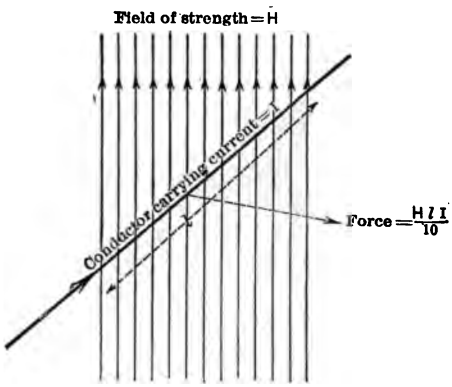



FIG. 95.—A Conductor of Length *l*, Perpendicular to the Magnetic Field and Carrying a Current *I*.

forces up and down respectively as shown by arrows and it is now seen that all conductors tend to turn the armature in the same direction, i.e., counter-clockwise.

*Torque Calculation.* To calculate the magnitude of this turning effort we must know the number of conductors lying in the magnetic field, the active length of each conductor (i.e., length of conductor under the pole face), strength of field in the air gap where the conductors are situated, and the current carried by the conductors. By the use of formula (1) we can calculate the force in dynes

on one conductor and this value, multiplied by the number of conductors situated in the magnetic field, gives the total force acting on the periphery of the armature.

*Active and Inactive Conductors.* It is to be noticed that those conductors lying in the interpolar space produce no turning effort; they are *inactive* conductors. When calculating the e.m.f. of a generator it was pointed out that

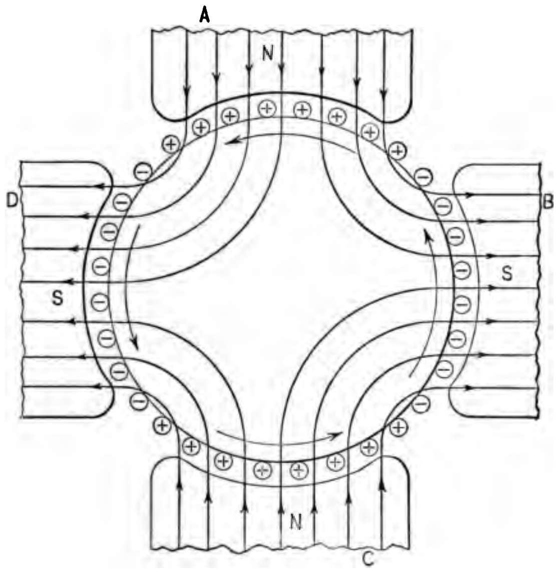



FIG. 96.—All Conductors Give Torque in the Same Direction.

these same conductors were inactive in the production of an e.m.f. in the armature; in fact *that portion of the armature winding which generates an e.m.f. when the machine is operated as a generator serves to produce torque when the machine is operating as a motor.* In calculating the e.m.f. of a generator it was found advisable to divide the active conductors into two parts, those lying directly under the pole face, where the field has its maximum intensity, and

those lying in the pole fringe where the field is weaker and nonuniform. The same division of conductors is advisable when calculating the torque of a motor.

*Example of Torque Calculation.* Suppose we wish to calculate the peripheral force on the armature shown in Fig. 96. The length of the pole face we take as 15 cm; the field we consider uniform and of a density equal to 8000 lines per sq.cm. There are 200 conductors on the armature of which 60% lie under a pole face and the current in each conductor is 20 amperes. The force (in dynes) per conductor is given by

$$\begin{aligned} f = Hl\,I/10 &= 8000 \times 15 \times 20 \times 20/10 \\ &= 240000 \text{ dynes} \\ &= .245 \text{ kg.} \end{aligned}$$

There are $200 \times 60\% = 120$ active conductors.

The peripheral force on the armature is therefore $.245 \times 120 = 29.4$ kg.

*Calculation of H.P. of a Motor.* If the peripheral speed of the armature is known, the output of the motor in ft.-lbs. per minute or horsepower is readily determined. If a body is exerting a force $f$, and moving in the direction in which this force is acting with a velocity $v$, then the rate of doing work is equal to $fv$. Hence, if we multiply the peripheral pull on the armature by the velocity of the armature periphery, the product obtained is equal to the amount of power which the motor is giving.

Let us consider a lap wound armature 4 ft. in diameter having 12 poles. The winding consists of 240 coils of 4 turns each and the length of the pole face is 10 inches. 60% of the conductors lie under the pole face where the flux density is 60000 lines per sq.in., and 15% lie in the pole fringe where the average density is 35000 lines per sq.in. What h.p. is the motor developing if the current flowing into the armature is 480 amperes and the machine is rotating 200 r.p.m ?

There are two things to find—the peripheral pull in lbs. and the peripheral velocity in ft. per min. The product of these two quantities divided by 33000 (the number of ft.-lb./min. in 1 h.p.) will give the h.p. of the motor.

As the armature is lap wound and the machine has 12 poles the winding must have 12 paths. Therefore the *current per path* $=480/12=40$ amperes, and this is the current in each conductor. The active length of each conductor is 10 inches. The total number of conductors $=240\times4\times2=1920$. Of these 60% (i.e., 1152), lie in a field of 60,000 lines per sq.in. and 15% (i.e., 288) lie in a field of 35,000 lines per sq.in.

The force in lbs, is therefore equal to

$$.885\times10^{-7}\times40\{(1152\times10\times60000)+(288\times10\times35000)\}=2970$$

The peripheral speed in feet per minute $= 4\times\pi\times200=2515$

The horsepower developed therefore $=\dfrac{2515\times2970}{33000}=226.$

**32. Current-torque Curves.** The relation between the torque developed by a motor and the current flowing through its armature winding is shown by a current-torque curve. This curve has different forms in motors with different styles of field windings.

*Shunt Motor.* The simplest case is that of the shunt motor. The field current of this machine is independent of the current flowing through the armature because its field windings are connected directly across the supply line, the voltage of which is assumed constant. Now if the field current of a motor is constant, the strength of its magnetic field is practically constant. Hence from equation (25) it is seen that the current-torque curve of a shunt motor must be a straight line, the torque being directly *proportional to the* armature current. This is shown

in Fig. 97 in which the result of a laboratory test is given. The curves are practically straight lines, curve $A$ being for a weak field (all of the field rheostat was in series with the field windings) and curve $B$ for a strong field (field rheostat " all-out ").

*Series Motor.* The series motor gives a different shaped curve because the field strength of such a motor depends upon the current flowing through its armature, the field and armature being connected directly in series. The

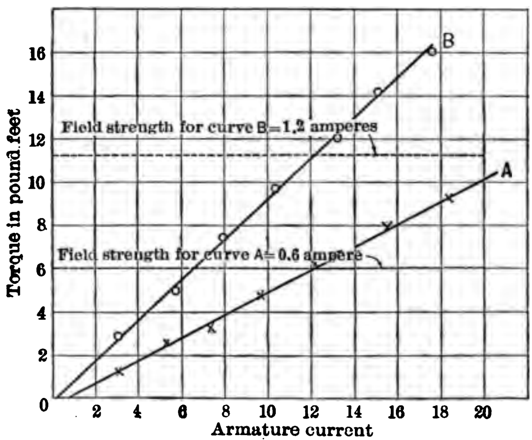



FIG. 97.—Current-torque Curves for Shunt Motor.

formula for torque involves the product of the field strength and armature current; when the field strength is directly proportional to the current through the field coils the *torque must vary as the square of the current.*

This is the case with the series motor at light loads. At values of armature current near full load (and for all currents of higher value), the field is approaching saturation so that the field strength is not proportional to the *current* through the windings. At very high values of *current the* strength of the field is practically independent

of the current and thus the torque-current curve tends to become a straight line, similar to that of a shunt motor. In Fig. 98 the results of a test are shown. The magnetization curve of the machine is given for reference, and it is seen that so long as the magnetization curve is a straight line the torque-current curve is parabolic in form but that for currents which begin to saturate the field (shown to be about 14 amperes in Fig. 98), the curve becomes less steep and approaches a straight line in form.

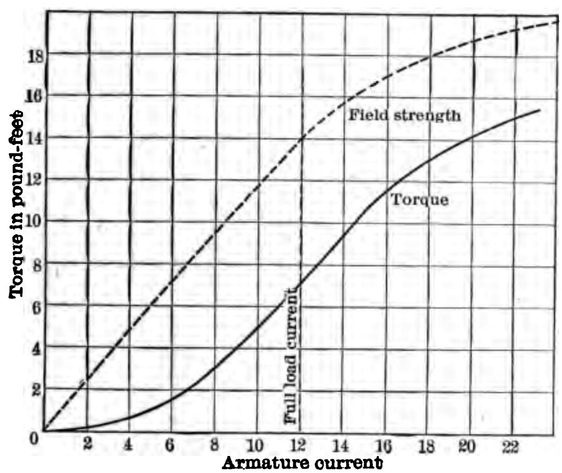



Fig. 98.—Current-torque Curve for Series Motor.

*Compound Motor.* The compound motor gives a current-torque curve the shape of which is intermediate between those of the shunt and series types. The curves for such a motor are given in Fig. 99; the field strength at zero armature current is given by the shunt coils only, but as the armature current increases the field strength increases somewhat, due to the m.m.f. of the series coils.

*Comparison of Different Motors.* The current-torque curves for three motors, all of the same rating, are given

in Fig. 100. At full load the speed for all three motors is the same and hence, as they give the same h.p. output at full load, the full load torque must be the same for all three. From these curves may easily be seen one point of superiority of the series motor for railway loads, where the torque necessary for starting a heavy train is excessive. It is seen from the curves of Fig. 100 that with 200% full load current (which might be safely put through the motor for

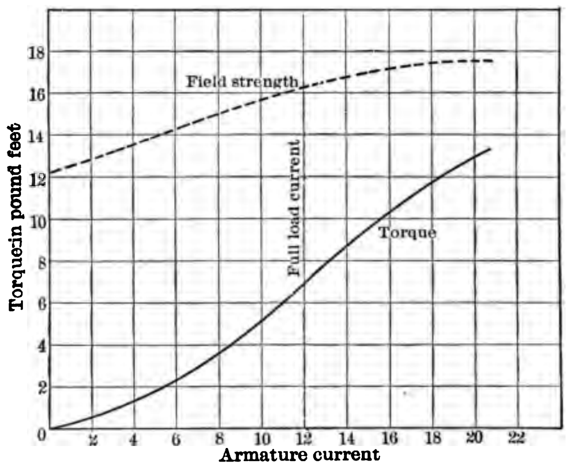



FIG. 99.—Current-torque Curve for Compound Motor.

the short time necessary for starting) the series motor gives much larger starting torque than either the shunt or compound motor.

**33. Speed-load Curves.** The principal factor which determines the selection of one type of motor or another for a certain class of work is the variation of its speed as the load on the motor is varied. The shape of the curve *showing* this variation of speed is very different for the *different types*.

*Comparison of Speed-load Curves.* In Fig. 101 are shown the speed-load curves for three motors having the same full-load speed; curve $A$ is that for a shunt-wound motor, curve $B$ is for a series and curve $C$ is for a heavily compounded motor. The shunt motor has a definite no-load speed and the speed drops somewhat as the load is increased; on the average shunt motor the drop from no load to full load may be between 5% and 15% of the no-load speed. The amount

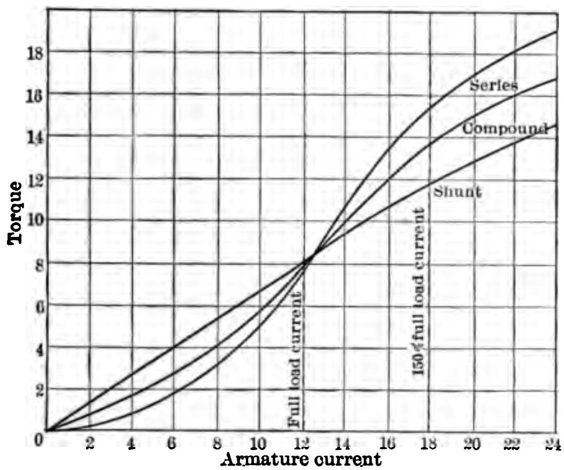



Fig. 100.—Comparative Current-torque Curves

of decrease in speed depends upon the armature resistance; the greater the resistance the greater the decrease in speed.

The curve for the compound motor has the same shape as that for the shunt motor but the speed decrease with increase of load is much more marked.

The series motor decreases its speed very much as its load is increased; as the load is decreased the speed increases rapidly and at very light loads the motor runs at speeds which are far above the safe speed. If all load

were taken off a series motor the speed would rise to such a value that the centrifugal forces brought into play would be so large that the winding would be thrown off the armature core and the commutator would probably be thrown to pieces.

*Limited Application of Series Motor.* This peculiarity of the series motor limits its use to those classes of service

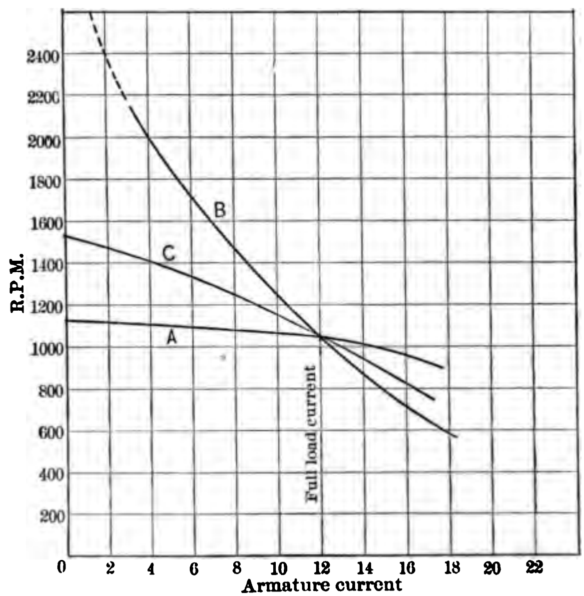



FIG. 101.—Speed-load Curves for *A*-shunt motor, *B*-series Motor, *C*-compound Motor.

in which the motor may be directly (or by gears) connected to its load so that under no condition would it be running without enough load to hold its speed down to a safe value. A series motor should never be belted to its load, because if the belt should run off the motor pulley, the motor would *immediately* start to " race " and in a few seconds would

be damaged. In electric railway installations the motor is *geared* to the car axle so that there is never any possibility of its running at excessive speeds.

*Development of Speed-load Formula.* The reasons for the different shapes of the speed load curves will now be taken up.

Let $E$ = the voltage of the line to which the motor armature is connected;
$e$ = the voltage generated by the armature winding, generally called the counter e.m.f. of the motor;
$R_s$ = the resistance of the series field;
$R_a$ = the resistance of the armature;
$I$ = the armature current;
$\Phi_{sh}$ = the field flux produced by the shunt field;
$\Phi_s$ = the field flux produced by the series field;
$\Phi$ = the total field flux $= \phi_{sh} + \phi_s$.
$N$ = the speed of rotation in r.p.m.;

The fundamental equation for determining the current in such a circuit as a revolving armature is obtained by equating the impressed force to the sum of the reacting forces of the circuit.

*Shunt Motor.* The counter e.m.f. and the resistance reaction both act against the impressed e.m.f. of the motor so we put

$$E = e + IR_a, \quad \ldots \ldots \quad (27)$$

from which we get

$$I = \frac{E - e}{R_a}. \quad \ldots \ldots \quad (28)$$

Now we know

$$e = K\Phi N, \quad \ldots \ldots \quad (29)$$

where $K$ is a constant involving the number of conductors on the armature, etc. So we have

$$I=\frac{E-K\Phi N}{R_a}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

or

$$N=\frac{E-IR_a}{K\Phi}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (31)$$

In the case of a shunt motor $\Phi$ is nearly independent of the armature current, $I$, so that by inspection of equation (31) it may be seen that the decrease in speed as the armature current increases is due to the factor $IR_a$. Also it is evident that the amount of decrease depends directly upon the value of the armature resistance.

*Compound Motor.* In the case of a compound motor the equation for speed becomes

$$N=\frac{E-I(R_a+R_s)}{K(\Phi_{sh}+\Phi_s)}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (32)$$

With an increase in $I$ (i.e., with increase in load) the speed of the compound motor must decrease because of two effects; the term $I(R_a+R_s)$ increases directly with the load and the term $K(\Phi_{sh}+\Phi_s)$ increases somewhat with the load. Although $\Phi_{sh}$ is independent of the current $I$, the term $\Phi_s$ is directly proportional to the current, $I$.

*Series Motor.* With the series motor we have

$$N=\frac{E-I(R_a+R_s)}{K\Phi_s}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (33)$$

This equation shows that the speed of a series motor must vary greatly as the load is changed. The flux $\Phi_s$ is directly proportional to the current, $I$, so we may write

$$N=\frac{E-I(R_a+R_s)}{KkI}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (34)$$

where $k$ is a constant depending upon the reluctance of the magnetic circuit and the number of turns in the series winding.

If the current is very small the denominator is correspondingly small and as a result the speed becomes very high. It is evident that *the counter e.m.f. of a motor must always be nearly as large as the impressed voltage* and, as the field flux of the series motor is very small at a light load, excessive speed is required to generate the necessary amount of counter e.m.f.

*Calculation of No-load Speed.* The no-load speed of a compound or a shunt motor is easily calculated. At no load there is practically no $IR_a$ drop so that the counter e.m.f. must be equal to the impressed e.m.f. The no-load speed may therefore be found by calculating what speed the motor would have to run (as a generator) to generate in its armature an e.m.f. just equal to that of the supply line.

**34. Effect of Armature Reaction on Speed.** So far nothing has been said regarding the effect of the armature m.m.f. upon the speed of the motor. When discussing armature reaction in Chapter III it was mentioned that armature reaction occurred to the same extent whether the machine is operated as a motor or a generator. But in a generator the armature current *flows in the direction of induced e.m.f.* and in the motor the armature current *flows against this induced e.m.f.* (called counter e.m.f.). So that the armature m.m.f. of the motor and generator are in opposite directions. In the generator the main field flux is twisted *in the same direction* as that in which the machine is rotating; in the motor the armature so reacts on the main field that it is twisted *against the direction of rotation.*

*Direction of Field Distortion.* This is shown in Fig. 102, which shows the direction of the twisted field for generator action in dotted lines and that for motor action in full lines. Hence, if the brushes are to short circuit that coil in

which no e.m.f. is being generated, they must be shifted *forward* in a generator but *backward* in a motor.

*Effect of Shifting Brushes.* When the brushes are shifted backward the armature m.m.f. of the motor may be split up into two components, one of which acts across the main field and the other tends directly to demagnetize

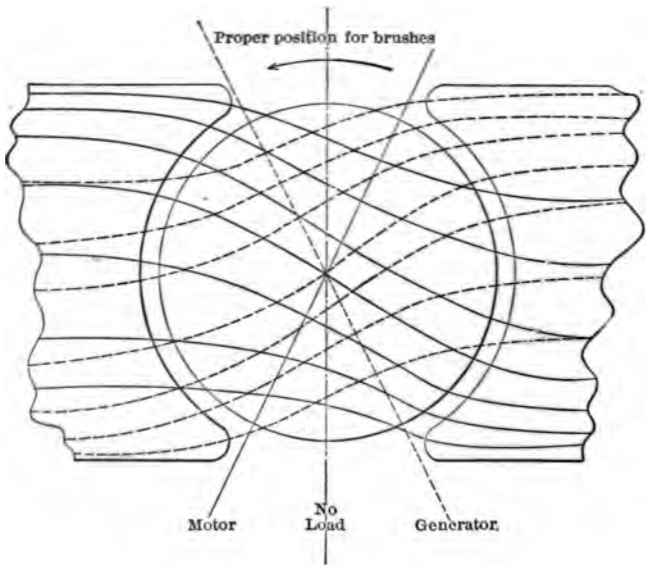



Fig. 102.—Field Shift in Motor and Generator, Caused by Armature Reaction.

the main field. In a motor with brushes shifted backward (i.e., against rotation) there is, therefore, an armature reaction which weakens the main field as the load increases. But a weakening of the field tends to make a motor speed up because, if the field is weakened, the counter e.m.f. decreases and so more current flows through the armature, tending to increase the speed.

*Armature Reaction and Resistance Act to Neutralize One Another.* This effect of field weakening may be about sufficient to overcome the effect of armature resistance drop, in which case the speed load curve will be nearly flat, giving no speed decrease with increase of load. If the brushes are shifted too far back, the weakening of the field caused by the armature reaction may be sufficient to make the motor *speed up* with increase of load.

If the brushes are shifted forward, the armature reaction tends to magnetize the main field and so the speed-load curve of the shunt motor with brushes having a forward shift, is nearly the same as that of a compound motor. This condition is never met in practice as the brushes of a motor spark viciously if shifted forward to any extent.

**35. Effect of Line Voltage on Speed.** If the voltage impressed on a motor varies, the speed of the motor may be expected to vary correspondingly. In the case of a shunt motor the field flux decreases with a decrease in the impressed voltage so that, in the formula for speed, $N=\frac{E-IR_a}{K\Phi}$, both $E$ and $\Phi$ vary and, if the field of the motor is not operated near saturation, the change in speed for a small change in line voltage is not marked. And if $E$ increases, $\Phi$ increases in nearly the same ratio so that, as $E$ increases, the speed does not increase very much.

In the case of a series motor there is no shunt field and thus for a *given current in the armature circuit,* the speed varies in nearly the same ratio as the impressed voltage.

The compound motor, having both shunt and series coils, has a change of speed, with change in line voltage, greater than that of the shunt motor and less than that of the series motor.

**36. Motors with Commutating Poles.** The problem of commutation is just as difficult to solve for the motor as for the generator. If a motor is not equipped with co

mutating poles the brushes must be shifted just as much in the motor as in the generator, if sparkless commutation is to be obtained.

Commutating poles, which are very important for the successful operation of a generator, are even more important in motor operation because the load variations are more sudden and violent. Practically all modern motors are fitted with commutating poles. The brushes of such motors are carefully adjusted before the machine is sent out from the factory and are generally held in place by a set screw or clamp; *the brushes on a commutating pole motor must not be shifted from this position,* as correctly determined in the factory.

*Effects of Various Conductors on Armature.* The poles and armature of a bipolar, commutating pole motor are shown in Fig. 103, and the direction of the e.m.f. induced in each conductor is indicated. If the brushes are in the neutral position (shown by line $AB$ in Fig. 103) there is no demagnetizing effect produced by the armature reaction and in each half of the armature winding there are a certain number of active conductors generating the necessary counter e.m.f.; these conductors are indicated by $X$ and $Y$ in Fig. 103.

The conductors marked $M$ and $N$ add nothing to the counter e.m.f. of the armature because in each half of the winding the e.m.fs. generated in these conductors neutralize each other. Considering the right-hand half of the armature in Fig. 103, it is seen that under the $S$ commutating pole there are two inductors with a "negative" e.m.f. and under the $N$ commutating pole there are two inductors generating a "positive" e.m.f.; hence in the right-hand side of the armature the effective counter e.m.f. must all be generated by the inductors marked $X$. The same reasoning shows that the only inductors generating the counter e.m.f. in the other path of the armature are those ·ed $Y$.

*Effect of Forward Brush Shift.* If the brushes are shifted *forward* to the plane $A'' B''$ the motor will slow down with an increase of load. This is due to three effects. The $IR_a$ drop increases with the load and so slows the

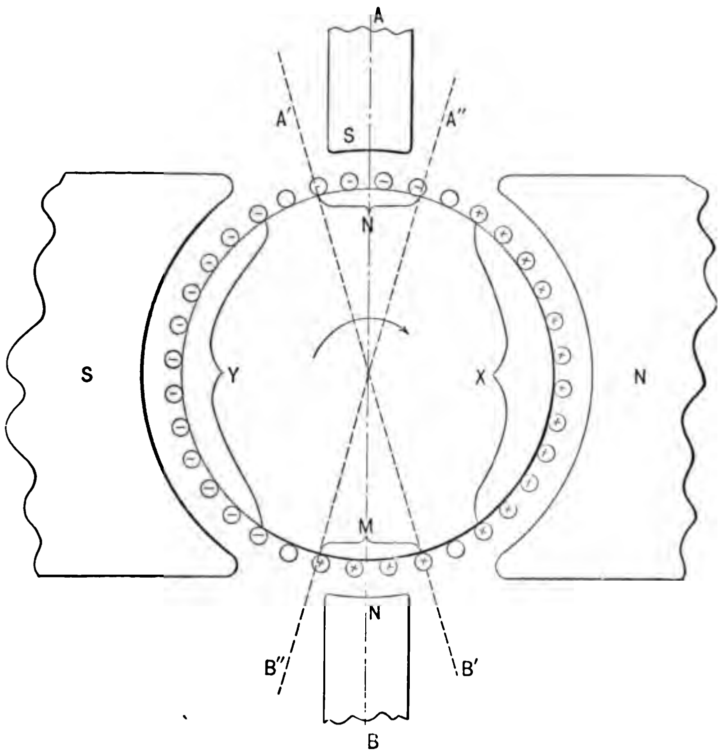



FIG. 103.—E.M.Fs. in Conductors of a Commutating-pole Motor.

motor down as shown before; the armature reaction in a motor tends to *magnetize the main field* when the brushes have a forward shift and so increases the counter e.m.f., thus causing a speed decrease; when the brushes are in the plane $A'' B''$ it is seen that the inductors marked $M$

and $N$ help in generating a counter e.m.f. in the armature winding. Those inductors marked $M$ evidently add their e.m.f. to that generated in the inductors $X$ and those marked $N$ add their e.m.f. to that generated by the inductors $Y$.

The e.m.f. generated in the inductors $M$ and $N$ is proportional to the load because the strength of field produced by the commutating poles is proportional to the load. The e.m.f. generated in the inductors $X$ and $Y$ is independent of the load (so long as the speed remains constant) but the counter e.m.f. of the armature winding as a whole tends to increase with a load increase because of this effect of the inductors $M$ and $N$. In fact the effect of the conductors $M$ and $N$ is just the same as though there were no commutating poles and the main field increased in strength with an increase in load. Hence these conductors and the armature reaction (with a forward brush shift) tend to make the motor act like a compound-wound motor which, as we know, has a speed-load curve which drops quite rapidly as the load is increased.

A certain commutating-pole motor ran at a speed of 1000 r.p.m. with no load; with the brushes in the plane $AB$ (Fig. 103), the full-load speed was 900 r.p.m. and with the brushes in the position $A'' B''$ the full-load speed was 670 r.p.m. This increase in speed decrease (670 r.p.m. as compared to 900 r.p.m.) was caused by the combined effect of the armature reaction and the commutating poles. When the motor was carrying full load with the brushes in the position $A'' B''$, they sparked badly. Why?

*Effect of Backward Brush Shift.* When the brushes are moved *backward* as shown at $A' B'$ (Fig. 103) the speed-load curve tends to become more nearly flat. The effects of the inductors $M$ and $N$ and of the armature reaction *both decrease* the counter e.m.f. of the armature as the load increases and thus tend to make the speed of *the motor increase* with a load increase. The effect of the

$IR_a$ drop, however, again tends to make the speed decrease as the load is increased so that the shape of the speed-load curve is determined by the relative magnitudes of these two effects.

If the armature resistance is high and the armature reaction and commutating poles relatively weak, the motor speed will fall off as the load is increased. In a motor having a smaller armature resistance the speed will actually rise with an increase of load; one motor tested increased its speed from 1000 r.p.m. at no load to 1080 at three-fourths load and before full load was reached the motor "ran away," i.e., the speed suddenly increased to such a value that the protecting devices in the armature circuit opened the supply line.

Of course, the brushes were sparking to some extent when in the position $A' B'$ but not as badly as when in the position $A'' B''$. In general it may be said, that, with a backward shift of the brushes, the operation of a commutating-pole motor is unstable; under certain conditions the speed of the motor may oscillate violently even when the load on the motor is constant. The motor mentioned above, with its main field weakened somewhat from its normal strength, when the brushes were in the position $A' B'$ "hunted" between speeds of 800 r.p.m. and 1200 r.p.m. until, finally, the protecting fuses blew and opened the circuit.

We may conclude, therefore, that on a commutating-pole motor the brushes must be accurately set in position; a shift of even one-half the width of one commutator bar from the proper position will often produce sparking and unsteady running.

**37. Motor Starting Rheostat.** When a motor armature is stationary, there can be no e.m.f. generated in its windings because there are no conductors cutting lines of force. If, then, the stationary armature of a shunt motor is connected directly to the supply line, the current which will

flow in the armature circuit may be calculated from the equation

$$E = e + IR_a, \quad \text{and as} \quad e = 0,$$

$$E = IR_a \quad \text{or} \quad I = \frac{E}{R_a}. \qquad \qquad (35)$$

*Necessity of Resistance for Starting a Motor.* Now the current calculated from this equation will be *ten or twenty times the full load current* and will be disastrous in its results.

Suppose a 110-volt motor, the full-load current of which is 40 amperes. The armature resistance of such a motor would be about 0.2 ohm. If the stationary armature were connected directly to the 110-volt line, the current through the armature would be $110 \div 0.2 = 550$ amperes, whereas the full-load current is only 40 amperes. The current of 550 amperes would burn the brushes, commutator, and winding, and also would probably blow the fuses in the supply line.

After the motor is running there is not an excessive current flowing through the armature because the current is limited by the counter e.m.f. But while the armature is accelerating this counter e.m.f. is small, and some other means must be employed to limit the starting current. This is the function of the **motor-starting rheostat,** or, as it is frequently called, the **starting box.**

A starting rheostat consists of a variable resistance, which may be gradually cut out as the motor speeds up and which can be cut out altogether when the motor has reached nearly normal speed. The total resistance of the starting box must be of such a value that, when it is connected directly across the motor supply line, the current which flows through it *will not be greater than about* 150% *full-load current* for the motor. The starting box is

sometimes designed so that it takes a current not greater than the full-load current of the motor.

*Example of a Proper Starting Rheostat.* Suppose that a starting box is desired for the 110-volt, 40-ampere motor mentioned in the previous paragraph. If the current in the armature circuit is to be 40 amperes at the start, the total resistance of the armature circuit (armature resistance and starting box) must be $110/40 = 2.75$ ohms. As the armature resistance is 0.2 ohm, the total resistance of the starting box must be $2.75 - 0.2 = 2.55$ ohms. The wire of which the starting box is made must be of sufficient size to carry safely 40 amperes during the short time required for the acceleration of the motor armature.

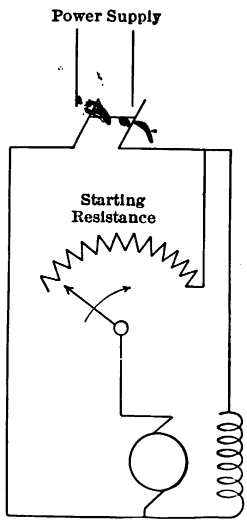



FIG. 104.—Connection of Resistance for Starting a Motor.

This resistance of 2.55 ohms would have taps at about five points so that it could be gradually cut out as the motor speeds up. The steps are not even; the above rheostat would probably be divided into steps of 2.55 ohms, then 1.7 ohms, 1.0 ohm, 0.4 ohm, and 0.2 ohm. The connection of the armature to the line through this variable resistance is shown in Fig. 104. The wires of which the starting box resistance is composed are imbedded in sand in the best type of starting boxes; they are then enclosed in fire-proof material so that if the operator keeps the starting resistance in the circuit for a longer time than that for which it was designed, thus overheating and possibly melting it, no fire risk occurs.

A starting box of good design and manufacture is shown

in Fig. 105. The lever, or arm by means of which the resistance is cut out as the motor speeds up, is so connected to a spring that it constantly tends to fly back to the " off " position, thus opening the armature circuit.

*Special Features of a Starting Rheostat.* There are two conditions under which the armature circuit should be opened, and the starting box, shown in Fig. 105, is designed

Fig. 105.—Front View of a Motor-starting Rheostat. Ward-Leonard Company.

to take care of these automatically. If too much load is put on the motor, a dangerously large current may flow through the armature circuit; under such a condition the armature should be opened, thus stopping the motor and warning the operator of the over-load. The **" over-load release "** of the starting box, shown in Fig. 105, actuates a stop which releases a small circuit breaker located on the face of the starting box, thus opening the circuit when the safe current is exceeded.

*Necessity of "No-voltage Release."* The "no-voltage release" permits the rheostat arm to fly back to the "off" position if the line voltage drops below a certain value. The object of this release is always to open the armature circuit when the supply line becomes "dead." When this occurs (as, for example, when the station circuit breaker on a feeder blows) the motor immediately slows down and stops. If the line is again made alive (circuit breaker re-set) an excessive current will flow through the stationary armature and may injure it. Of course, the over-load release would open the circuit under such conditions, but these over-load releases are designed only to break currents of about the same magnitude as the full-load rating of the motor. As was shown on page 172, the current which flows through a stationary armature when it is connected directly to a normal voltage line is many times the full-load current and if the small circuit breaker on the front of the starting box were depended upon to break such large currents it would soon be damaged.

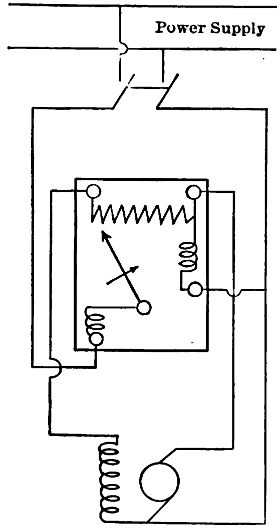



FIG. 106. — Connections of "Over-load release" Magnet and "No-voltage release" Magnet of a Motor-starting Rheostat.

*Connections for Starting Rheostats.* The solenoid which operates the no-voltage release is connected (in series with a suitable resistance) directly across the supply line, and the solenoid which operates the overload release is connected in series with the motor. The connections of such a rheostat to the motor and supply line is shown in Fig. 106. In starting a motor the arm must not be moved over too

rapidly else the over-load release will blow; neither must it be moved over too slowly else the resistance wire in the rheostat is likely to be melted. The contact points on the face of the rheostat should be kept clean, as must also the sliding contact, or " shoe," on the rheostat arm.

**37. Speed Control of Motors.** It is often necessary to vary the speed of a motor according to the changing requirements of the load. To make the electric motor suitable for railway service, operation of machine tools, etc., it must be possible to change quickly and easily its speed through a wide range, and the scheme for obtaining this variation in speed must be such that the motor operates with a good efficiency at any one of the speeds required.

*Possibility of varying Speed.* By inspection of equation 31, page 164,

$$N=\frac{E-IR_a}{K\Phi},$$

it is seen that the speed may be varied by a change in the impressed voltage $E$, the resistance of the armature circuit, $R_a$, or the value of the field flux, $\Phi$. The loss in heat in the armature circuit is equal to $I^2R_a$ (where $R_a$ is the resistance of the armature circuit), and if this quantity is large the motor must necessarily be inefficient; speed control by the addition of resistance in the armature circuit is therefore seldom used and will not be discussed here.

*Multiple Voltage Control.* In the system using multiple voltage control, the power line consists of several wires, and the voltage between various pairs is different. In one system four wires are used to distribute power to the motors and the power supplied to these four wires is obtained from a set of three generators. The various voltages obtainable by using different pairs of supply wires are shown in Fig. 107. The voltage impressed on the armature in this system may be varied in steps from 60 volts

to 250 volts and the speeds obtainable would vary in about the same proportion so that the highest speed obtainable would be about four times the lowest speed. This would be called a 1 : 4 speed control.

This scheme is used in the operation of motors for driving machine tools. If a high speed is desired for a certain operation on a lathe, the motor is connected to the 250-volt line, and, when lower speeds are desired, the motor is connected to one of the other pairs of wires, having a suitable voltage. Such a system of speed control involves complicated wiring and controllers for the motors but its advantage lies in the fact that the motors operate at a comparatively high efficiency at any one of the speeds obtainable.

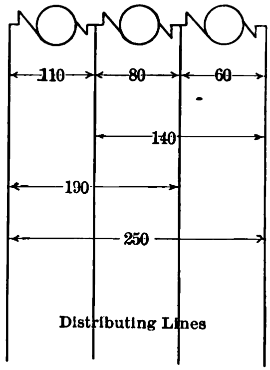



FIG. 107.—Power Distribution Scheme for Multiple Voltage-speed Control.

*Speed Control by Field Variation.* Another important method for obtaining various speeds consists in weakening the field of the motor. This is called *field control.* When first discussing the speed-load curves of motors it was shown that, under any condition of operation, the counter e.m.f. developed in the armature winding must be nearly equal to the impressed voltage. If now the impressed voltage is maintained constant and the field flux is varied, it is evident that the above condition can be fulfilled only if the speed of the motor follows the changes in field strength: a high speed corresponding to a weak field and vice versa.

The amount of variation which can thus be obtained from a shunt motor of ordinary design is not very great; the twisting of the main field by the armature reaction

is not enough to be objectionable when the main field is operated somewhere near saturation, but when this field is weakened, the effect of the armature reaction is much exaggerated and the brushes will spark badly unless properly shifted with every change in load.

*Commutating Poles used with Field-weakening Control Scheme.* The type of motor best adapted for speed variation by the field control method is the commutating pole motor and practically all motors intended for service where a variable speed is desired are equipped with commutating poles. In such motors the commutating pole provides the flux required for sparkless commutation, irrespective of the strength of the main field. Such motors are designed for a speed range as great as 1:6; ordinarily, however, the speed variation obtainable is not greater than 1:3 or 1:4.

*Variable Speed Motor Compared to a Constant Speed Motor.* The torque obtainable from a variable speed motor is greatest when the main field has its greatest strength, i.e., at minimum speeds. As the speed is increased by field weakening, the torque decreases in about the same ratio as the speed increases. This is due to the fact that the torque of a motor is proportional to the product of the armature current and the field density; the safe armature current is nearly the same at high speeds as at low speeds so that the torque goes down as the speed goes up. The product of torque and speed is practically the same whatever the speed and this means that the motor has the same capacity in horsepower over its whole speed range.

Now a motor to give a certain output must be of larger size the slower the speed; the size of all variable-speed motors is, therefore, larger than that of standard constant-speed motors of the same horsepower capacity. A field frame designed for a standard constant-speed 5-h.p. motor would be used in the construction of a 3-h.p. variable-speed motor: other sizes would be in about the same ratio.

*Comparison of Field Control and Multiple Voltage Methods.* The field-control method of speed variation results in the efficient operation of the motor and the wiring of the power supply to the motor is so much simpler than that of the multiple voltage system that it is much preferred to the latter. The number of running speeds in the multiple-voltage scheme shown in Fig. 107 is limited to six, while the number obtainable when using field control depends only upon the number of contact points in the field rheostat of the motor; as many as 40 or 50 speeds are thus available with the rheostats ordinarily employed.

The multiple-voltage control may employ more or less field control, however, in which case the number of running speeds obtainable is greater than when field control alone is used. The chief advantage of the multiple-voltage control over the straight field control lies in the smaller size of motor required for a given horsepower capacity.

**38. Speed control of Railway Motors.** The speed control of railway motors is accomplished by the variation of the voltage impressed across the motor terminals by what is called the **series-parallel control.** There are always at least two motors on each electric car and sometimes there are four, all of the same rating. When the car is first started, all motors are connected in series, through a starting resistance, to the 600-volt line, the trolley or third rail being one side of the line and the track the other side. The controller (which is simply a rotating switch) has marked on its face various points, the number of these points depending upon the type of motor equipment.

*The Various Steps Used in Starting.* The first three points are generally "resistance points," i.e., while the controller handle is pointing to any one of them more or less of the starting resistance is connected in series with the motors. On the fourth point the two motors are connected in series with each other and directly to the line. This is called a "running point" because no power is

being wasted as heat in the starting resistance and so the equipment is operating at a fair efficiency. The motors are next thrown into parallel connection and some of the resistance is again put in series with them. While the motors are being changed from series to parallel connection, the controller handle is moving through the "transition points" and the controller handle is so designed that it

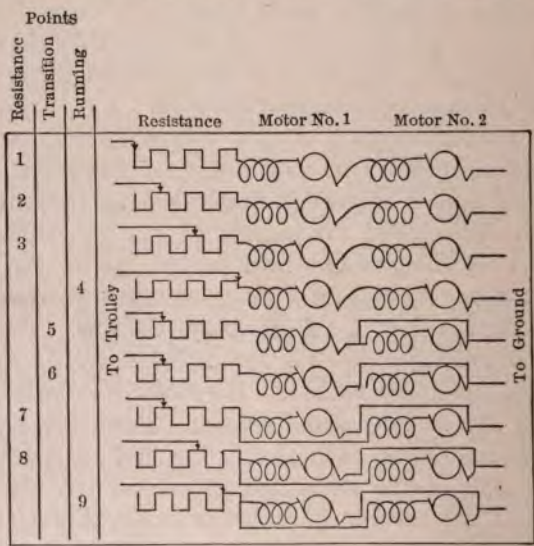



FIG. 108.—Connections for Series-parallel Control of Railway Motors.

will not remain on one of these points unless held there. When the transition points have been passed through and the motors are connected in parallel, the resistance is again cut out in two "resistance points" and, finally, the two motors are each operating on the full line voltage. This is the second "running point." The various connections used in the system of control are well shown in Fig. 108.

*Disadvantage of the Above Scheme.* The disadvantage in this scheme of control is that while going through the

transition points the tractive effort on the car, and hence its acceleration, is much decreased. On points 5 and 6, Fig. 108, the tractive effort will evidently be less than that on point 4 because on these points only one motor is active; the other has no current flowing through it. The acceleration of a car equipped with this system is somewhat uneven.

*The Bridge System of Control.* In modern railway equipments a different set of connections are used in accelerating the car, which is known as the **bridge control.** A diagram of the connections used in this scheme is shown in Fig. 109. Here *T* stands for a trolley connection and *G* for a ground connection.

At first the two motors are connected in series with all the resistance and there are three steps in cutting out this resistance as before. When the "bridge" is put in the first running point is reached. Next come the transition points, on the first of which the connection *A* is removed, in the second, connection is made to the trolley and ground as indicated, and in the third, the bridge connection is removed.

During this transition period each motor continues to carry the same current as it did on running point 4. The starting resistances are so designed that when the bridge is removed no sudden change takes place in the current through the two motors. Then on points 5, 6, and 7 the resistance is again cut out, and in point 8 the second running speed is reached. All modern railway equipments are being furnished with this bridge system of control as it gives a more uniform acceleration than the older method shown in Fig. 109.

*Possibility of Field Weakening.* If the motors are equipped with commutating poles, two other running points may be obtained. After point 4 has been reached a resistance is shunted across each motor field, thus weakening the field and increasing the motor speed and giving what we may call running point 4*a*. In changing from point 4

to the first transition connection, these shunts are removed and not connected again until after point 8 has been reached. At present these shunts are not much used.

*The Railway Controller.* A typical railway controller is shown in Fig. 110, and in Fig. 111 is given an enlarged view showing some of the contact fingers bearing on the

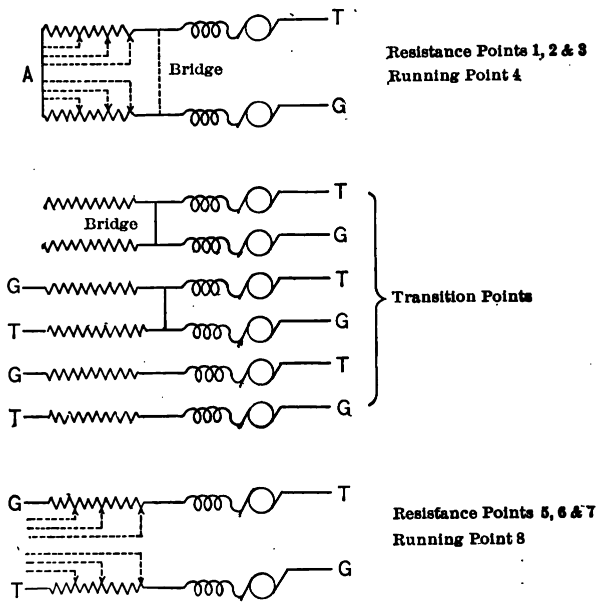



FIG. 109.—Connections for Bridge Control of Railway Motors.

copper segments which are carried on the main cylinder of the controller. As these fingers break contact with the segments, an arc is formed between a finger tip and a segment tip and, if not taken care of, the arcing would soon damage the controller. The controller is so designed that the arc *is formed in a magnetic field* which tends to lengthen the arc and so makes it rupture as soon as it is

formed. This feature of the controller is called the **magnetic blow-out.** Also the segment tips and fingers are so made as to be easily replaced by new ones when they have been burned so much as to be unserviceable.

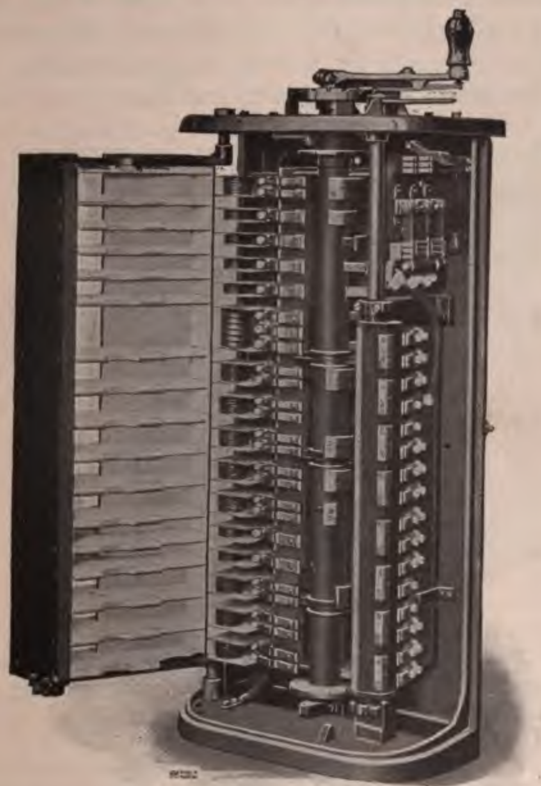


FIG. 110.—Inside View of Railway Controller.

**39. Use of a Flywheel with a Compound Motor.** The rate at which power is required by some kinds of machine tools is very irregular; in the punch press or forming press for example almost no power is required until the die comes

in contact with the metal to be punched or formed. The rolling mill is another instance of a tool calling for an irregular power supply.

If the mass of the moving parts is not very great in such machines the power consumption of the driving motor will be very irregular. Fig. 112 illustrates this point; the full line curve shows the current consumption of a motor driving a shears for cutting large iron bars.

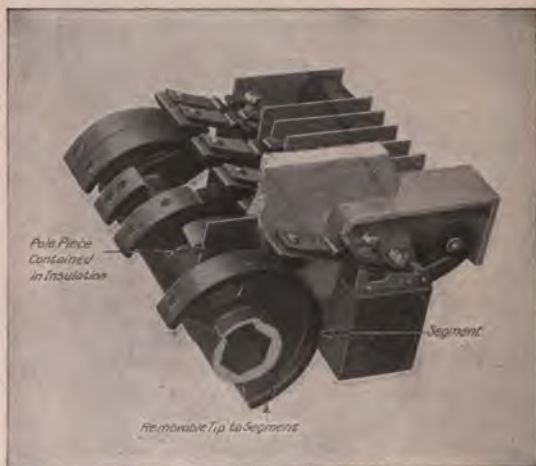



FIG. 111.—Some of the Contact of a Railway Controller. A magnetic "blow-out" scheme is used to prevent serious arcing at the contacts. General Electric Company.

Now the motor in which such a current is flowing must be made sufficiently large to commutate successfully the *greatest value* of current, as at $A$. If the motor driving the shears were a compound-wound motor with a comparatively large number of turns in its series field (say 30%–40% compounding), and a heavy flywheel is put on the same shaft with the armature, the current to the motor, while

doing the same work as before, will be given by the dotted curve of Fig. 112, in which the maximum value is much less than it was before. In fact this motor equipped with the flywheel might be much smaller than the one without the flywheel. The motor through which current $A'$, Fig. 112, flows need be only about two-thirds as large as if curent $A$ were the current input.

*Effect of the Flywheel.* The action of the motor equipped with a flywheel is as follows: At time $t_1$, Fig. 112, the load on the motor suddenly increases and so causes the motor to begin to slow down. As it slows down, the rotating

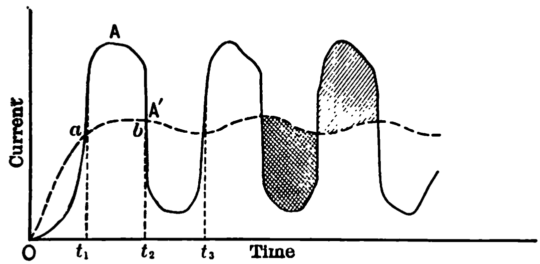



FIG. 112.—Current Consumption of a Compound Motor, with and without Flywheel.

flywheel is slowed down also and so gives up some of its kinetic energy. During the time from $t_1$ to $t_2$, Fig. 112, the electrical input to the motor is not as great as the power demanded by the load, hence the motor slows down and the retarding flywheel assists the motor to carry the load. During this slowing down process, the current input to the motor must increase somewhat.

If at the time $t_1$ the speed is 1000 r.p.m., and at the time $t_2$ the motor has slowed down to 800 r.p.m. and the speed-load curve of the motor is as given in Fig. 113, the current must increase during the same period from $OD$ to $OE$. In Fig. 112, $at_1$ equals $OD$ of Fig. 113 and $bt_2$

of Fig. 112 is equal to *OE* of Fig. 113. At the time $t_2$ the power demanded by the load is less than the input to the motor and so the motor begins to speed up and to increase the energy stored in the flywheel; the current begins to decrease at the same time. At the time $t_3$ the motor has regained its original speed of 1000 r.p.m. and the current has fallen to the value *OD*. The single-hatched area in Fig. 112 represents the amount of energy which the retarding flywheel gives up when the load is heavy and the double-

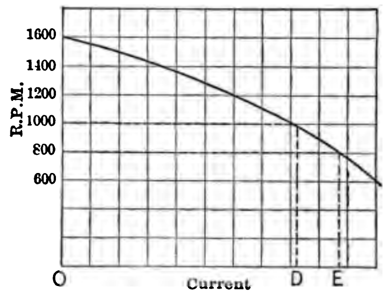



FIG. 113.—Speed-load Curve of Heavily Compounded Motor.

hatched area represents the energy which the motor returns to the flywheel when the load is light; these two areas are equal.

This use of a heavy flywheel to equalize the input to a motor supplying an intermittent load is becoming quite general; it decreases the size of motor required and makes the operation of the generating station much easier. This last consideration is of importance only when the size of the motor is somewhere near that of the generator supplying its power.

# CHAPTER V

## THE EFFICIENCY OF A DYNAMO-ELECTRIC MACHINE

**40. Importance of a High Efficiency.** If the amount of electrical power put into a motor is measured and the mechanical power output is measured during the same time, the **efficiency** of the motor may be obtained by finding *the ratio of the output to the input.* In just the same way the efficiency of a generator is the ratio of the output to the input; in this case, however, the input is mechanical power and output is in the form of electrical power. Both input and output must be expressed in the same unit before the efficiency may be calculated. Suppose, for example, that the input to a small electric motor is 1 kw. and the output is 1 h.p. The output in turns of kilowatts is .746, so that the efficiency is $\frac{.746}{1}=74.6\%$. Or we might say the input is equal to 1.34 h.p. so that the efficiency is equal to $\frac{1}{1.34}=74.6\%$.

*Example of the Operating Cost of a Low-efficiency Machine.* The efficiency of an electrical machine is one of its most important characteristics. To illustrate the importance of a high efficiency for a motor let us consider the case of a factory requiring 100 h.p. to run the machinery installed in it. If the motor used to drive the shafting has an efficiency of 90% the necessary input when the motor is giving off 100 h.p. is equal to $100 \div .90 = 111$ h.p. which is equal to 83 kw. Suppose the price of power is \$.06 per kw.-hr. (prices vary between \$.04 and \$.15 per kw.-hr.,

according to the size and location of the power station and the amount of power used by the customer). The cost of power per ten-hour day would be equal to $\$.06 \times 83 \times 10 = \$49.80$.

If now the motor has an efficiency of 80% we may calculate in the same way the cost for power to run the factory a ten-hour day and find it to be $56.00. The difference in cost in operating these two motors for a year would be $1860.00, and this is more than the cost of the motor. This one example serves to show how important the efficiency of a dynamo-electric machine is commercially.

**41. Losses and Their Variation with Load.** *Mechanical Losses.* There are several so-called *losses* in any electric machine. For example, in the operation of a motor some of the power input is used in overcoming the friction of the shaft turning in the bearings, the friction of the brushes on the commutator, and the friction of the revolving armature on the air (called *windage*). These are usually designated as mechanical losses.

*Electrical Losses.* There are also other losses due to ohmic resistance, hysteresis, and eddy currents; these are called electrical losses. As losses due to ohmic resistance may be mentioned the $I^2R$ losses in the field windings, in the armature windings, and in the brushes and brush contacts. Then there are the hysteresis loss in the armature core, and the eddy-current losses in the armature core and pole faces, where power is used and given out in the form of heat.

*Variation of Losses with Load.* Some losses are independent of the load the machine is carrying and some vary with the load. If the speed of a machine (either motor or generator) remains constant as the load varies, we may assume that all of the mechanical losses are constant, i.e., independent of load. If they are measured at any one load they may be regarded as having the same value for any other load.

When the speed of a machine varies as the load changes, *the mechanical losses may be considered to vary directly with the speed.* If, for example, on a series motor, the mechanical losses are measured and found to be 800 watts when the armature is turning 1200 r.p.m., they may be assumed to equal 400 watts when the motor is turning 600 r.p.m.

The current flowing in a shunt field is nearly independent of the load. In the case of a shunt motor connected to a constant potential line the shunt field current will be entirely independent of the load and hence *the $I^2R$ loss in the field coils will be constant.* This loss will be larger when the machine is first started than when it has run a sufficient length of time to get warmed up; in Chapter I the effect of an increasing temperature upon the resistance of a conductor was noted.

The current in the armature and series field of a motor (or generator) is proportional to the load the machine is carrying; the ohmic resistance loss is, therefore, *proportional to the square of the load* and if the $I^2R$ loss is plotted as one co-ordinate with the load as the other, the curve will be a parabola.

*Loss at the Brush Contacts.* The resistance of the brush contacts (carbon brushes are assumed) is not a constant quantity but depends upon the current density at the contact surface. If the current density is low, the resistance is high and vice versa. This is entirely different from the armature and field circuits; except for the temperature change effects the resistances of these circuits are constant and not affected by the current density. It has been found by experiment that the resistance of brush contacts varies somewhat with the current density at the contact surface; the $IR$ drop through two brush contacts in series may be calculated approximately by the formula,

$$IR \text{ drop} = .8 + (.2 \times \text{ampere per sq.cm.}) \quad . \quad . \quad (36)$$

The normal current density at full load is 5 amperes per sq.cm. so that the brush contact drop $=.8+(.2\times5)=1.8$ volts, *for both brushes together*. This drop is nearly the same on all sizes of machines as it depends only upon the *current density* in the brush contacts and not upon the current itself; the current density is practically the same for all sizes of machines.

The loss due to brush contact resistance is small compared to the other losses in a machine and it is often computed by taking *the IR (contact resistance) drop as equal to 2 volts at all loads.* This makes the calculation of brush contact $I^2R$ very simple and even though it is a rough approximation, but very little error is produced in the final result. In a motor taking 40 amperes at full load the contact resistance loss may be approximately obtained by putting $I^2R$ loss $=40\times2=80$ watts, etc.

*Hysteresis and Eddy Current Losses.* In a shunt generator or motor *the hysteresis and eddy current losses are nearly independent of the load providing the speed does not change with the load.* They depend upon the flux density in the armature core and the speed with which the armature revolves. The speed will generally change somewhat as the load changes and these losses may be considered to vary directly with the speed, the same as the mechanical losses.

*Stray Power.* All of the mechanical losses, and the hysteresis and eddy current losses (commonly called *core loss*) are measured together and the whole loss is called the stray power. The stray power therefore comprises all mechanical losses and core losses and may be assumed to vary directly with the speed.

*Loss Curves.* We have, then, four losses to take into consideration when determining the efficiency of a motor or generator; the stray power, which varies slightly with the load, the shunt field loss which is generally independent of the load, the brush contact resistance loss which varies *directly* with the load, and the armature and series field

(if there is any) $I^2R$ loss which varies with the square of the load.

These various losses are shown plotted as curves in Fig. 114. The results are taken from a test of a 5 h.p. shunt motor and are about right for any continuous-current machine of this capacity. The curve marked "total loss"

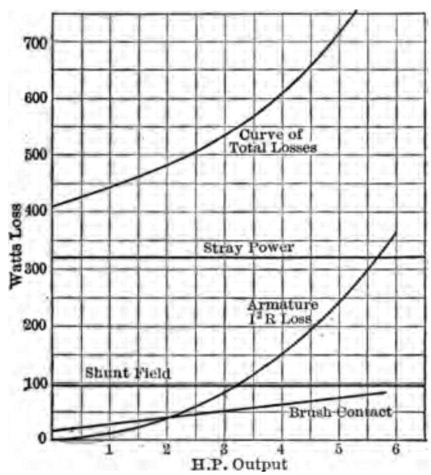



FIG. 114.—Loss Curves of a Motor.

is plotted by adding the ordinates of the other four curves, the significance of which is indicated in the figure. The shunt field loss is 97 watts at all loads, and the stray power is 320 watts at no load and practically the same at full load; the brush contact resistance loss is 3 watts at no load and 80 watts at full load, the no-load armature $I^2R$ loss is less than one watt and at full load it is 242 watts.

**42. Calculation of Efficiency from Loss Curves.** If such a set of curves is given for any machine its efficiency curve may be at once obtained. The input to any electric machine must evidently be equal to the output plus all

the losses occurring in the machine; hence the efficiency may be obtained by using the formula

$$\text{Efficiency} = \frac{\text{output}}{\text{output} + \text{losses}}. \quad . \quad . \quad . \quad (37)$$

At full load the output of the motor referred to in the previous paragraph is equal to $746 \times 5 = 3730$ watts.

The input must be $3730 + (242 + 97 + 80 + 320) = 4469$ watts.

Hence the full load efficiency $= \frac{3730}{4469} = 83.6\%$.

When the output $= 4$ h.p., the efficiency $= \frac{2982}{2982 + 627} = 82.7\%$

When the output $= 3$ h.p., the efficiency $= \frac{2238}{2238 + 550} = 80.3\%$

When the output $= 2$ h.p the efficiency $= \frac{1492}{1492 + 495} = 75.1\%$

When the output $= 1$ h.p., the efficiency $= \frac{746}{746 + 455} = 62.1\%$

When the output $= 0$ h.p., the efficiency $= \frac{0}{430} = 0\%$

Ordinarily the loss curves are not obtained in terms of horsepower output but in terms of the armature current and hence the efficiency curve is obtained in terms of the armature current.

*Efficiency Determination without Actually Loading the Machine.* To determine the efficiency of an electrical machine it is not necessary to actually load it; some method of determining the various losses is all that is required.

*This is a great advantage in the testing of large machines;* for example if a 1000-h.p. motor were to be tested, two difficulties would be encountered if it were attempted to actually load it up to its rated capacity. First it would be difficult to find some way of putting a load of 1000 h.p. on the motor and then of measuring it accurately, secondly it would require about 1000 kw. of power to run the test and even though this power were available, *it would all be wasted in running the test* unless some special "pump-back" test* was used.

**43. Obtaining Data for the Determination of Efficiency.** To determine the losses no facilities for loading the machine are required and but little power is used in making the test. To get the stray power the machine is run as a motor with no load. When the rated voltage is impressed on the armature, the field rheostat is adjusted until the rated speed is obtained and then the input to the armature circuit is measured.

The resistance of the armature winding is determined and the armature $I^2R$ loss (with no-load current flowing) is calculated. This subtracted from the no-load input to the armature gives the no-load stray power and this is assumed as the same for all loads. The resistance of the shunt field circuit is measured and the shunt field $I^2R$ loss is found. The brush contact resistance is calculated after the area of the brush contact has been measured and the brush contact $I^2R$ loss may be determined from the formula discussed in a previous paragraph.

* The term "pump-back" test is used to designate a test in which two similar machines are being tested at the same time. In such a case one machine is generally used as a motor to drive the other machine as a generator; the power from the generator is "pumped" back into the line from which the motor is drawing its power, hence the power actually used, even when both machines are operating at approximately full load, is only that amount necessary to supply the losses in the two machines.

*Example of Efficiency Prediction.* The readings obtained from such a test upon a 100-h.p. motor would give results about as follows:

Rated voltage $=230$ volts;
Rated current $=350$ amperes;
Shunt field resistance (hot) $=75.2$ ohms;
Armature resistance (hot) $=.0112$ ohm;
Armature current (running light) $=15.1$ amperes;
Area of brush contacts $=70$ sq.cm.;
Current density full load $=5$ amperes per sq.cm.;
Drop at the brush contacts (full load)
$$=.8+(.2\times 5)=1.80 \text{ volts;}$$
Drop at the brush contacts (half load)
$$=.8+(.2\times 2.5)=1.30 \text{ volts, etc.;}$$
The armature $I^2R$ loss at no load
$$=15.1^2\times .0112=2.5 \text{ watts;}$$

Stray power (no load)
$$=(230\times 15.1)-\left\{2.5+15.1\left(.8+\left(.2\times\frac{15.1}{70}\right)\right)\right\}=3465 \text{ watts;}$$

Shunt field loss $\left(\frac{E^2}{R}\right)=1060$ watts.

From the data the curves of Fig. 115 were plotted. Then the total loss curve was constructed and from this the efficiency was readily computed. The shape of the efficiency curve is about the same for any electric motor or generator. The efficiency is low at light loads, reaches a fair value at half-load and, from this point up to one and one-quarter load, is practically constant. The full-load efficiency of large machines may be as high as 94%, while for small machines of a few horsepower it is nearer 80%.

*Determination of Efficiency from Name-plate Data.* The full-load efficiency of a motor can always be approximately determined from the rating given on its name plate. The A.I.E.E. rules specify that, among other things, the name plate of a motor shall give the voltage and current for which the machine was designed at full load, and the output in horsepower (if the machine is a motor).

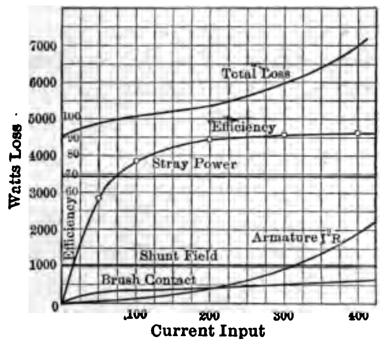



FIG. 115.—Loss Curves and Efficiency Curve for a Motor.

Suppose, for example, that the rating of a certain machine from the name plate is 110 volts, 38.5 amperes, 5 h.p.

The watts input, full load $=110\times38.5=4350$ watts.
The watts output, full load $=5\times746=3730$ watts.
Hence the full-load efficiency $=3730\div4350=85.7\%$.

# CHAPTER VI

## ELEMENTARY PRINCIPLES OF ALTERNATING CURRENT

**44. Alternating Currents — Wave Shape — Frequency.** An alternating current is one which periodically changes its direction of flow, assuming alternately positive and negative values. The current generally completes a **period** (complete **cycle** of values) in a very short time, perhaps one-fifteenth of a second or less. Also the sequence of values assumed during the negative half of the cycle is exactly similar to that of the positive half. In other words if the instantaneous values of current are plotted with time for the other co-ordinate, a wave is obtained, the two halves of which are similar in a peculiar way. In Fig. 116 is shown one complete cycle of an alternating current; if the loop $B$ is moved back on the time axis to $B'$, then $A$ and $B'$ are symmetrical with respect to the time axis. Practically all alternating current and voltage waves have this characteristic symmetry.

*Alternation-Frequency.* One-half a cycle is called an **alternation**; in Fig. 116 the time $CE$ is called the **period** of the alternating current and the number of periods passed through by the current in one second is called the **periodicity** or **frequency.** A current of a frequency of 60 cycles for example, passes through 60 cycles per second; the frequency is expressed sometimes, however, in alternations per minute and we might say that this 60-cycle current had a frequency of 7200 *alternations per minute.*

*Frequencies in Common Use.* The frequencies in common use for lighting and power purposes are 60 cycles and 25

cycles per second. In the early days of alternating current engineering a frequency of 133 was adopted as the standard and recently it has been recommended that a frequency of 15 cycles per second be used for railway motors of a certain type. Sixty cycles is as low as can be employed for lighting purposes; if a lower frequency than this is used, the resultant flickering of the lamp becomes tiring to the eye.

For the transmission of messages by wireless telephony and telegraphy a frequency of many thousand cycles per second is used; machines have been built for this work which generate as high as 200,000 cycles per second.

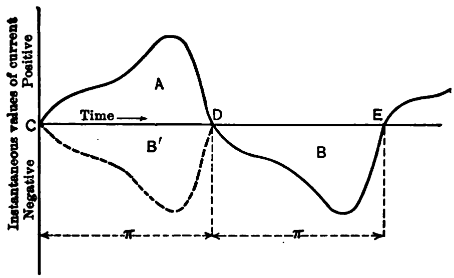



FIG. 116.—Curve Illustrating Mirror Symmetry.

*Shape of Wave.* The shape of the curve representing an alternating current or e.m.f. is sometimes very important. In nearly all commercial circuits the forms of voltage and current waves are simple sine curves as shown in Fig. 117; there will always be more or less departure from the simple sine form caused by the presence of sine waves of higher frequency than the fundamental.

*Upper Harmonics Affect Wave Shape.* A current which has approximately the form of a 60-cycle sine wave is likely to be distorted by the presence of other sine waves of frequencies of 180 cycles per second, 300 cycles per second, etc. These higher frequency currents are called upper

**harmonics,** being some multiple of the fundamental wave; the 180 cycle is the third harmonic of the 60-cycle wave and the 300-cycle wave is the fifth harmonic, etc.

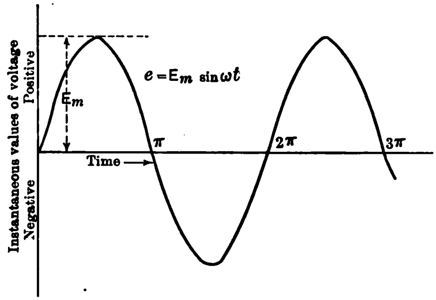



FIG. 117.—A Sine Curve of E.M.F.

In all ordinary cases of distorted waves *only the odd harmonics appear;* when a curve has the symmetry mentioned in the previous paragraph it may at once be assumed that no even harmonics are present.

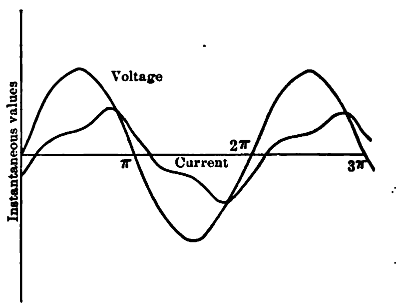



FIG. 118.—Voltage and Current Forms in an a-c. Circuit having an Iron Core Inductance.

*Typical Wave Shapes.* In Figs. 118 and 119 are shown ~~me typical wave forms. Fig. 118 shows an e.m.f. wave ~~rly pure sine form. The current wave in the same

figure represents the exciting current of a transformer; its shape indicates the presence of the third and fifth harmonics. Fig. 119 shows the e.m.f. wave of an alternating current generator which the manufacturers guaranteed would give a sine wave; this shows how poorly a machine may sometimes be designed. Certain types of alternating current apparatus would not operate at all if supplied with power from such an alternator; if this machine were used in making tests upon a circuit in which condensers were

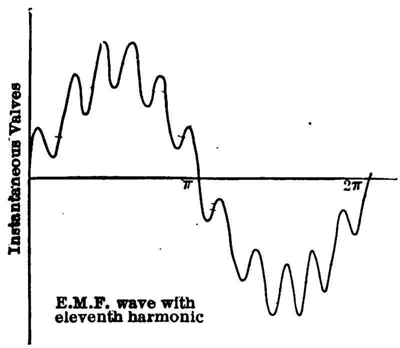



FIG. 119.—Reproduction of an e.m.f. Wave from an a-c. Generator, Supposed to Give a Sine Curve.

used, the results obtained would be very difficult to interpret.

**45. Virtual * Values—Form Factor.** As the magnitude of an alternating current varies from instant to instant, assuming all values between its maximum positive and maximum negative values, it is apparent that we must establish some method of determining what is the *virtual numerical value of such a current* in amperes. The equivalence between the ampere of continuous current and the ampere of alternating current is determined by the effect

* The word *virtual* has recently been adopted by the A.I.E.E. to signify the maximum value $\div \sqrt{2}$. Previously the term *effective* value had been used in this sense.

of the two currents in heating a certain resistance. Or we may say that *an alternating current has an effective value of one ampere when it produces heat in a certain resistance at the same rate as heat is produced in the same resistance by one ampere of continuous current.*

*Virtual Value of a Sine Wave.* It may be proved experimentally or by the calculus, that if the alternating current is a simple sine wave (i.e., no upper harmonics present) as shown in Fig. 117, the virtual value in amperes, is equal to the maximum value in amperes, divided by $\sqrt{2}$. That is, if we have an alternating current of the form

$$i=I_m \sin \omega t; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (38)$$

where $i$ = the instantaneous value of the current;
$I_m$ = the maximum value of the current;
$\omega = 2\pi$ times the frequency;

then $I$, the virtual value of such a current is given by the relation

$$I=I_m/\sqrt{2}=I_m \times .707 \quad . \quad . \quad . \quad . \quad . \qquad (39)$$

*Virtual Value of a Complex Wave.* When the curve of current is not a simple sine wave the relation between the virtual and maximum values can not be represented by a simple expression. But, in any case, we have the rule that the virtual value of any alternating current is equal to *the square root of the average square of the instantaneous values.* This is expressed in some texts by the letters R.M.S., meaning "root mean square."

What has been said in regard to current waves holds good also for voltage waves so we have, when $e=E_m \sin \omega t$,

$$E=E_m/\sqrt{2}=E_m \times .707 \quad . \quad . \quad . \quad . \qquad (40)$$

where $e$ = the instantaneous value of the voltage;
$E_m$ = the maximum value of the voltage;
$E$ = the virtual value of the voltage.

*Form Factor.* It is sometimes desirable to know the *ratio of the virtual value of a wave to its average value.* The ratio is called the **form factor** of the wave.

The average value of a simple sine wave may be obtained by measuring the area between the curve and the $X$ axis

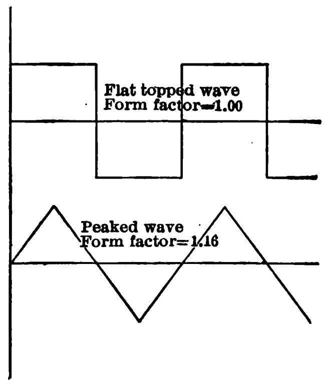



FIG. 120.—Extreme Cases of Wave Distortion. Actual waves are not as bad as these.

and then dividing this area by the base of the curve. The average value of a sine wave is found to be equal to

$$E_m \times \frac{2}{\pi} \quad \text{or} \quad .636 E_m.$$

Hence the form factor is equal to

$$E_m/\sqrt{2} \div E_m \times \frac{2}{\pi} = 1.11.$$

For a wave more peaked than a sine wave the form factor is greater than 1.11 and for a flat topped wave it is less than this value. Two extreme cases are given in Fig. 120.

**46. Vector Representation.** It is inconvenient to always use the curve diagram for representing currents and e.m.fs.; a much simpler method is by means of the *vector diagram.*

*Use of a Rotating Vector.* It is a familiar fact that a sine curve may be properly represented by a rotating vector, the length of which is equal to the maximum value of the sine wave and the speed of rotation of which (measured in radians per second) is equal to $2\pi$ times the frequency of the alternating current.

In Fig. 121 the vector $OA$ is supposed to rotate in the counterclockwise direction with the angular velocity $\omega$, where $\omega = 2\pi f$. Time is reckoned as zero when the vector $OA$ coincides with the $X$ axis so that at the end of the

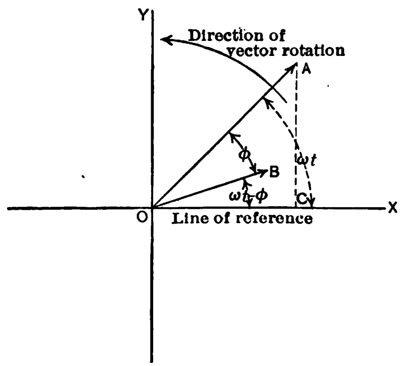



Fig. 121.—Vector Representation of Voltage and Current.

time $t$ the vector has swept through the angle $\omega t$. At this time the instantaneous value of the current, which the vector diagram is supposed to show, is $OC = OA \cos \omega t$ and as the length of $OA$ has been chosen equal to the maximum value of the current it is evident that the projection of the vector $OA$ on the $X$ axis represents, at any time, the instantaneous value of the current expressed analytically by the equation $i = I_m \cos \omega t$.

Projections on the $X$ axis to the right of the $Y$ axis represent positive values of current while those to the left represent negative values of current.

**47. Phase Displacement—Power—Power Factor.** If an alternating e.m.f. is applied to a circuit, a current will flow which will, in general, be of the same shape as the e.m.f. wave. There are some cases where this is not true but they will not be considered until later.

Although the current and e.m.f. will, in general, be of the same shape, they will not usually be *in the same phase.* In Fig. 122 are shown the curves of e.m.f. and current in two different circuits, one taking a **leading current** and the other a **lagging current.**

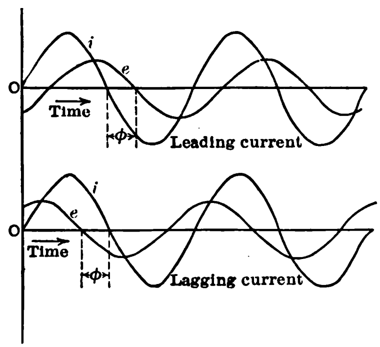



FIG. 122.—Curves Showing Leading Current and Lagging Current.

In both of these circuits, the current is said to be *out of phase* with the voltage; the phase difference is given by the angle $\phi$ in both cases. A current *in phase* with the voltage would have its maximum and minimum values at the same time as the voltage. Such a current is shown in Fig. 123.

*Lead and Lag on Vector Diagram.* The idea of lead and lag is expressed in a vector diagram by the relative position of the two vectors used to represent the current and e.m.f. In Fig. 121 is shown a voltage (vector $OA$)

*OB* which represents a current in an inductive circuit, on which the voltage *OA* is impressed.

If the equation of the voltage is written $e=E_m \cos \omega t$ then evidently the proper equation for current (referred to the same time origin as the e.m.f.) is $i=I_m \cos(\omega t-\phi)$ and $\phi$ in the **phase difference** of current and e.m.f.

*Power Factor.* The power being used at any instant in an a-c. circuit is given by the product of the values of e.m.f. and current at the instant considered. It is proved in elementary texts on alternating currents that the power used in any circuit, in terms of virtual voltage and current is given by the formula $Watts=EI \cos \phi$.

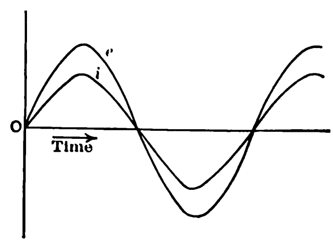



FIG. 123.—Current and Voltage in Same Phase.

The product, $EI$, is sometimes called *apparent power* and evidently *cos $\phi$ is that quality by which the apparent power must be multiplied to give the true power.* It is therefore called the **power factor** of the circuit.

**48. Active and Reactive Components of Voltage and Current.** It is generally necessary to use the expression " voltage in phase with current " or " in-phase voltage " and similar expressions. When the voltage and current are represented as vectors, we resolve one on the other and so get *two components* at right angles to one another. In Fig. 124 the two possible schemes are represented.

In (*a*) the voltage *OE* is projected on the current vector *OI.* The component *OA* is in phase with the current and

the component $AE$ is 90° out of phase with the current. In ($b$) the current is resolved into two components, $OA$ in phase with the voltage $OE$, and $AI$ at 90° with the voltage. The component $OA$ is called the "watt component" or "power component," or "in-phase component" in various books. The component $AI$ (or $AE$) is called the "wattless component" or "quadrature component" or "out-of-phase component."

All of these terms are more or less vague and ambiguous. We shall use the words *active* and *reactive* to designate the two components. That component of the voltage in phase with the current we shall call the **active component**

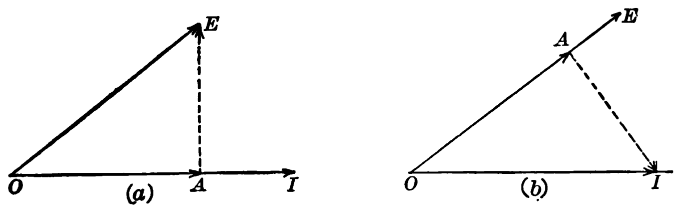



FIG. 124.—Vector Diagrams Showing Active and Reactive Components of Voltage and Current.

**of the voltage** or merely **active voltage.** The component of voltage 90° out of phase with the current we shall call the **reactive component** of the voltage or **reactive voltage.**

Similarly the component of current in phase with the voltage will be called the **active current** and the component of current at 90° with the voltage will be called the **reactive current.**

*The product of the voltage and active current (or current and active voltage) gives the active power of the circuit.*

*The product of the voltage and reactive current (or current and reactive voltage) gives the reactive power of the circuit.*

When the single term **power** is used in connection with an a-c. circuit *active power*, or *true power* is always signified.

The three terms we shall use in connection with power are *apparent power*, *power* and *reactive power*.

We have also

$$\text{Apparent power} = E\,I. \qquad (41)$$

$$= \text{voltage} \times \text{current}.$$

$$\text{Power} = E \cos \phi \times I \text{ or } E \times I \cos \phi. \qquad (42)$$

$$= (\text{active voltage} \times \text{current}) \text{ or } (\text{voltage} \times \text{active current}).$$

$$\text{Reactive power} = E \sin \phi \times I \text{ or } E \times I \sin \phi \qquad (43)$$

$$= (\text{reactive voltage} \times \text{current}) \text{ or } (\text{voltage} \times \text{reactive current}.)$$

*Example.* To illustrate these definitions and terms an example is given. Suppose that a certain circuit carries a current of 20 amperes when the impressed voltage is 100 volts and that the phase difference between the voltage and current vectors is 37°, e.i., $\phi = 37°$. Now if $\phi = 37°$ $\cos \phi = 0.8$ and $\sin \phi = 0.6$.

Hence

| | |
|---|---|
| Voltage | $= 100$ |
| Current | $= 20$ |
| Active voltage | $= 100 \times 0.8 = 80$ |
| Reactive voltage | $= 100 \times 0.6 = 60$ |
| Active current | $= 20 \times 0.8 = 16$ |
| Reactive current | $= 20 \times 0.6 = 12$ |
| Apparent power | $= 100 \times 20 = 2000$ volt-amperes |
| Power | $= 80 \times 20 = 1600$ watts |
| | $= 100 \times 16 = 1600$ watts; |
| Reactive power | $= 60 \times 20 = 1200$ watts |
| | $= 100 \times 12 = 1200$ watts. |

**49. The Wattmeter—Power Measurement.** From what has been said in the previous paragraph it is evident that the power used in an a-c. circuit cannot be determined by employing a voltmeter and ammeter as would be done in a continuous current circuit. If it were possible to determine $\phi$, then the power could be calculated from the readings of these instruments, but to determine $\phi$ directly it is necessary to use either a laborious method of curve plotting or else the use of special instruments as the oscillograph or power factor meter; these instruments are not generally available.

*The Wattmeter.* An indicating instrument has been designed, however, and is constantly used on a-c. circuits, which will actually indicate the $EI \cos \phi$ value for any circuit; it is called the **wattmeter.** There are two coils in this instrument, one fixed and made of a few turns of comparatively large conductor and the other, movable and made of many turns of fine wire. This movable coil is mounted on a shaft, fitted with jewelled bearings, so that it turns inside the stationary coil. It carries an indicating finger which moves over a suitably graduated scale.

It may be proved theoretically and experimentally that such an instrument, when properly calibrated, actually does read $EI \cos \phi$, $E$ and $I$ being the virtual values of voltage and current in the circuit to which the wattmeter is connected. Fig. 125 shows a well known type of portable wattmeter. The current coil terminates in the heavy copper lugs on the left of the instrument and the potential coil is connected to the two smaller posts seen at the upper end of the instrument case.

*The rating of a wattmeter is always given in terms of volts and amperes;* the current coil can stand only a certain number of amperes and the potential coil only a certain pressure in volts; and if the power factor of a circuit is low it is readily seen that *the capacity of the meter in watts on*

such a circuit is low. In fact it often occurs in the laboratory that a wattmeter is burned out when the indicating finger shows only a fraction of the full scale deflection; the low

Fig. 125.—A Portable Wattmeter. Weston Electrical Instrument Co.

reading is due to the low power factor of the circuit and is low in spite of the fact that the current through the meter is dangerously high and may be burning the windings.

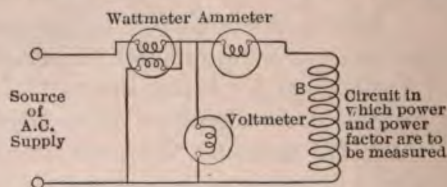



Fig. 126.—Connection of Meters for Measurement of Power and Power Factor.

*Connection of Meters for Determining Power and Power Factor.* Fig. 126 shows the connection of an ammeter, voltmeter, and wattmeter to a circuit in which it is desired to know the power consumption and power factor. When it is desired to obtain the highest possible accuracy of

measurement, care must be exercised in the relative arrangement of the meters. In the connection diagram in Fig. 126, for example, the wattmeter, $W$, is recording not only the amount of power used in the circuit being tested but also the power used up in the voltmeter $V$ and the ammeter $A$. The power used in each of these instruments will generally be less than 5 watts, hence if the circuit $B$ is using several hundred watts, no appreciable error is introduced by the power consumption of the meters. A more complete discussion of this point may be obtained from books specializing in a-c. measurements.

The power factor of circuit $B$ is obtained at once by the ratio of the wattmeter reading to the product of the readings of the voltmeter and ammeter.

**50. Resistance of an Alternating Current Circuit.** When an alternating e.m.f. is impressed upon a circuit consisting of incandescent lamps, water rheostats, straight wires, etc., the amount of current which flows is just the same as would flow if a continuous e.m.f. of the same voltage were impressed. It is said that such a circuit possesses only *ohmic resistance;* this is a poor term but is used by some writers and, therefore, is here given. It is used to designate a circuit in which the only opposition to the flow of the current *is offered by the conductor* of which the circuit is composed; we shall call this the **conductor resistance.** In many circuits this is not the only resistance which the circuit offers, as will be explained hereafter.

*Effective Resistance.* We shall use the term **effective resistance** of an a-c. circuit in general; it may (as in the case cited above) be the same as the conductor resistance and in other cases it may be much more. The effective resistance can be less than the conductor resistance, only in very special cases.

For any a-c. circuit we may put

$$\text{Watts} = I^2R, \qquad \text{(44)}$$

which says that the power used up in the circuit is equal to the product of the (current)$^2$ and a certain constant, $R$, *which we call the effective resistance.* This equation constitutes the definition of the term effective resistance. From the definition it is evident that the effective resistance of any circuit may be obtained by dividing the wattmeter reading of the circuit by the squared value of the ammeter reading.

Now a wattmeter reads, for any circuit, $EI \cos \phi$, and $E \cos \phi$, is evidently the component of the impressed force which is in phase with the current. But if

$$\text{Watts} = I^2R = EI \cos \phi,$$

it is evident that

$$IR = E \cos \phi \qquad \ldots\ldots\ldots \quad (45)$$

which gives us another definition for effective resistance; it is that quantity which multiplied by the current, gives the component of the impressed force used up in phase with the current, or active voltage.

*Effective Resistance Increased by Hysteresis Loss, Radiation Loss, etc.* Let us suppose a circuit consists of a coil of wire around an iron core and that an alternating current is flowing through the coil; the iron core, being magnetized first in one direction and then in another, will have to take in enough energy to supply the hysteresis and eddy current losses. This energy must be supplied by the electric circuit which is magnetizing the core and if a wattmeter is placed in the circuit it will indicate not only the power used in heating the wire of which the magnetizing coil is made, *but also that used in heating the iron core.*

Hence, when the resistance of such a circuit is determined by dividing the wattmeter reading by the (current)$^2$ it will evidently be more than the conductor resistance by an amount depending upon the magnitude of the loss in

the iron core. In a small coil with an iron core used in the laboratory for testing purposes, the conductor resistance is 0.70 ohm and the effective resistance varies from 4 ohms to 30 ohms, depending upon the current and frequency. In the case of an aerial conductor used as an antennæ for sending messages by wireless telegraphy, the conductor resistance may be quite small, but the effective resistance is much greater *owing to the energy that leaves the circuit in the form of electric waves.*

*Skin Effect.* When the alternating current is of high frequency another effect comes into play to increase the resistance of a conductor; it is called the **skin effect.** It is found that, when the conductor is of appreciable diameter (say, 0.25 inch) and the frequency is high (say several thousand), the current does not utilize all of the cross-section of the conductor but flows almost entirely in a thin layer of the conductor near the surface. In fact, for very high frequency currents a solid rod is not appreciably a better conductor than a thin tube of the same material of the same diameter. Of course, this effect increases the effective resistance of a conductor.

**51. Method Used for Solving A-C. Circuits.** In a circuit containing only resistance (no inductance or capacity) the impressed e.m.f. is all used up in overcoming the **resistance reaction.** This is expressed by Ohm's law, written in the form

$$E = IR,$$

where $E$ is the impressed e.m.f. and $IR$ is the resistance reaction (explained in next paragraph). This idea of equating the impressed force to the reactions existing in the circuit will be very useful in discussing inductance and capacity. We shall attempt to show how all problems in a-c. circuits may easily be solved by use of the general equation,

$$\textbf{Impressed force} = \textbf{sum of all reactions in the circuit.} \qquad (46)$$

*Resistance Reaction.* The resistance reaction, of course, opposes the flow of current so when the current is positive the resistance reaction is negative and vice versa. As this reaction is always equal to $iR$ ($i$ being the instantaneous value of the current) it must be a sine curve similar to the current. But if it is a sine curve it may be properly represented by a rotating vector, in phase opposite to the vector representing the current in the circuit. In Fig. 127, $OI$ represents the current in a non-inductive circuit and $OA$ the resistance reaction. As the impressed force must always be equal and opposite to the sum of the reactions in the circuit it is properly shown in Fig. 127 by the vector $OE$.

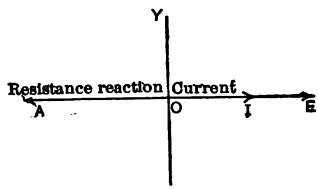



FIG. 127.—Vector Diagram of Resistance Reaction.

This construction brings the current in phase with the impressed force as we know it should be in such a circuit.

**52. Inductance.** Suppose a circuit is made up of 1000 feet of No. 10 copper wire running out 500 feet and back, and that there is no other resistance in the circuit except that of the wire, which will be approximately one ohm. If 100 volts of alternating e.m.f. of frequency 60 cycles were impressed on this circuit the current which would flow would be about 100 amperes; the only reaction which the circuit would offer to the impressed force would be a resistance reaction.

If now this same piece of wire is wrapped up in the form of a coil, say about one foot in diameter, and 100 volts (alternating and of the same frequency as before) is

impressed, the amount of current which will flow will be only a few amperes. Now the resistance of the circuit is evidently the same as it was before and therefore the resistance reaction, $IR$, can be only a few volts. The question which immediately arises is this: if the sum of the reactions of any circuit is equal to the impressed force *what reaction, besides that due to resistance, is there in this coil of wire?*

There must be some other reaction because the $IR$ will be only a few volts (say 10) and the impressed force is 100 volts. The other reaction which exists and assists the resistance reaction in balancing the impressed force is that due to the *self-induction* of the circuit and we call it the **inductance reaction.**

*Principle of Induced E.M.F.* Faraday was the first experimenter to show that when the number of magnetic lines threading a coil of wire was varied, an e.m.f. was induced in the coil. He also discovered that the magnitude of this induced e.m.f. was proportional to the *rate at which the magnetic field through the coil was varying.* Now it makes no difference whether the magnetic field is produced by some source apart from the coil or by the coil itself. When the magnetic field (the variation of which is inducing an e.m.f. in the coil) is produced by a current flowing in the coil itself, the e.m.f. is called *the e.m.f. of self-induction.*

*Direction of induced E.M.F.* This e.m.f. of self-induction is always in such a direction that it *opposes the change in the current producing it.* When the current is increasing in a positive direction (i.e., the rate of change of current is positive) the e.m.f. of self-induction is in the negative direction and when the rate of change of the current is negative the e.m.f. of self-induction is in the positive direction. This e.m.f. of self-induction which opposes any change in the current through a coil we call the inductance reaction.

*Form of Inductance Reaction Curve.* It can be shown both geometrically and analytically that when the current is a sine wave the rate of change of current is a wave of similar shape but displaced 90° in phase. In Fig. 128 are shown two curves, the full line curve being that for an alternating current, and the dotted one that for the rate of change of this current. The inductance reaction is equal to $L$, the coefficient of self-induction of the coil, multiplied by the rate of change of current and is just opposite in phase to the latter curve. Hence the inductance reaction is similar in form to the rate of change in current curve and

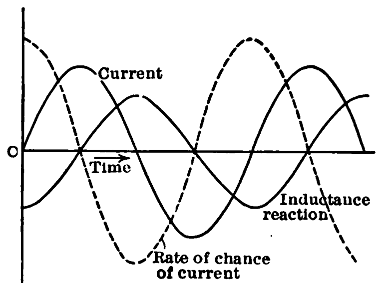



FIG. 128.—Curve Diagram of Inductance Reaction.

opposite to it in phase and it is shown in Fig. 128 by the curve marked "inductance reaction."

*Inductance Reaction as a Vector.* As this is a sine curve in form it may be represented by a rotating vector. Hence in the coil of wire connected to the 100-volt alternating current line, there are offered two reactions to balance the impressed voltage, the resistance reaction and the inductance reaction, both of which may be represented by vectors. We have seen before that the resistance reaction is in *phase opposition* to the current and Fig. 128 shows the inductance reaction to be 90° *behind the current.* Fig. 129 shows these two reactions at $OA$ and $OB$ and their vector resultant at $OC$.

Now as the impressed force must be equal to the resultant of the reactions and opposite to this resultant in phase, it is properly shown at $OE$. It is seen that the result of such a construction is to show the current *lagging behind* the impressed force and we know that this is really the condition in an inductive circuit.

*Magnitude of Current in an Inductive Circuit—Impedance.* It may be shown that if $f$ is the frequency of the current in the coil, $L$ the coefficient of self-induction in henries and $I$

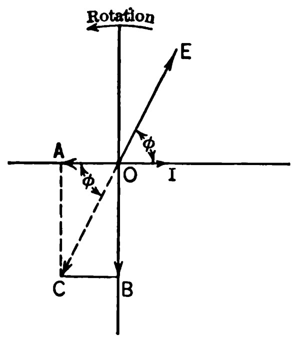



FIG. 129.—Vector Diagram of Inductance Reaction.

the current in amperes the inductance reaction is equal to $2\pi fLI$ volts.

Now evidently

$$OC = OE = \sqrt{OA^2 + OB^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (47)$$

$$= \sqrt{\overline{IR}^2 + \overline{2\pi fLI}^2}$$

$$= I\sqrt{R^2 + \overline{2\pi fL}^2} = I\sqrt{R^2 + X^2}, \quad . \quad (48)$$

where $X = 2\pi fL$.

The term $2\pi fL$ is called the **reactance** of the circuit and the expression $\sqrt{R^2 + \overline{2\pi fL}^2}$ is called the **impedance** of the circuit. It is sometimes designated by the letter $Z$.

It is seen that by transposing the terms in equation (48) we get the equation

$$I=\frac{E}{\sqrt{R^2+\overline{2\pi fL}^2}}=\frac{E}{Z}. \quad . \quad . \quad . \quad . \quad (49)$$

It may be seen from Fig. 129 that in such an inductive circuit,

$$\cos\phi=\frac{OA}{OC}=\frac{IR}{\sqrt{\overline{IR}^2+\overline{2\pi fLI}^2}}=\frac{R}{\sqrt{R^2+\overline{2\pi fL}^2}} \quad . \quad (50)$$

The reactance and impedance of a circuit *are both measured in ohms,* the same as resistance. This is really an improper use of the unit but it is used throughout this book because it is common practice.

*Example to Illustrate Inductance and Impedance.* To illustrate the idea of inductance and impedance let us suppose a circuit has a resistance of 100 ohms and a self-induction of 0.5 henry and that the frequency of the current in the circuit is 60 cycles. What is the reactance of the circuit and how much is the impedance? As the reactance (in ohms) is given by the equation $X=2\pi fL$ we have

$$X=2\pi\times60\times0.5$$
$$=188 \text{ ohms.}$$

The impedance

$$Z=\sqrt{R^2+X^2}$$
$$=\sqrt{100^2+188^2}$$
$$=213 \text{ ohms.}$$

If an e.m.f. of 110 volts is impressed on this circuit the current which will flow is given by the equation

$$I=\frac{E}{Z}=\frac{110}{213}=0.517 \text{ ampere.}$$

The inductance reaction $= 2\pi fLI = 188 \times 0.517 = 97.2$ volts.

The resistance reaction $= IR = 100 \times 0.517 = 51.7$ volts.

The resultant of these two reactions is equal to $\sqrt{97.2^2 + 51.7^2} = 110$ volts and this serves to check the accuracy of our calculation as we know that the sum of the reactions must be equal to the impressed force.

The power factor of this circuit is equal to

$$\cos \phi = \frac{\text{resistance reaction}}{\text{total reaction}} = \frac{51.7}{110} = 0.47.$$

The amount of actual power used in the circuit is equal to $I^2R = 0.517^2 \times 100 = 26.7$ watts. The apparent power (volts $\times$ amperes) used in the circuit is equal to $110 \times 0.517 = 56.9$ volt-amperes. As we know,

$$\text{Power factor} = \frac{\text{watts}}{\text{volt-amperes}}$$

$$= \frac{26.7}{56.9} = 0.47,$$

which is the same as that obtained above and so checks our calculations.

*Current Depends upon Frequency.* If the frequency impressed on the circuit were only 25 cycles, the reactance would be only $2\pi \times 25 \times 0.5 = 78.5$ ohms, and the resistance would be the same as it was before. The impedance would be 127 ohms and the current would be $110/127 = 0.867$ amperes. The power used would be $I^2R = 75$ watts and the volt-amperes $110 \times 0.867 = 95.4$. The power factor would be $\frac{75}{95.4} = 0.787$, which is greater than it was before. If the frequency were increased to 133 cycles the reactance would be 418 ohms, the impedance 430 ohms, and the current $\frac{110}{430} = 0.256$ ampere. The power used in the circuit would be 6.56 watts and the power factor would be 0.233.

From these calculations we see that the result of increasing the frequency in an inductive circuit is to decrease the current, the power used, and the power factor. A decrease in frequency produces the opposite effects.

**53. Capacity.** Two conducting plates, separated by a dielectric, constitute what is called a **condenser.** This name is given to such an arrangement because it seems to *condense,* or hold, the electricity which runs into it.

*Construction of a Condenser.* An ordinary condenser consists not of one pair of plates but of several hundred or more plates of tin-foil, separated by sheets of a special grade of paper which has been impregnated by some insulating compound. Every other sheet of tin-foil is connected together and these form one terminal of the condenser; the remaining sheets are connected together to form the other terminal.

*Condenser in a C-C. Circuit.* When a condenser is connected to a c-c. line, there is an instantaneous rush of current until the condenser is *charged* and then no more current flows unless the voltage of the line changes. If the condenser is disconnected from the line and its two terminals connected together by a conductor, there is a sudden rush of current through the wire and the condenser becomes *discharged.*

*Charge and Discharge Current Curves.* The charge and discharge currents ordinarily last for only a small fraction of a second; typical curves are shown in Fig. 130. The full line curves represent the currents in a paraffine condenser and the dotted line curves those for a mica condenser. The substance which separates the metal plates of a condenser is called the dielectric; the difference in the shape of the two sets of curves in Fig. 130 is due to the characteristics of the two different dielectrics, viz., paraffine and mica.

*Condenser in an A-C. Circuit.* Now if a condenser is connected to a line of alternating e.m.f., there will be

current running into, or out of, the condenser continually. It was stated above that *when the e.m.f. on the terminals of a condenser changes, current will flow either into, or out of, the condenser.* If the voltage *increases* the current will be *into* the condenser and when the voltage *decreases* current will flow *out* of the condenser.

*Current in a Condenser in an A-C. Circuit.* It may be shown mathematically that if the voltage impressed on a condenser is a sine wave the current flowing into the con-

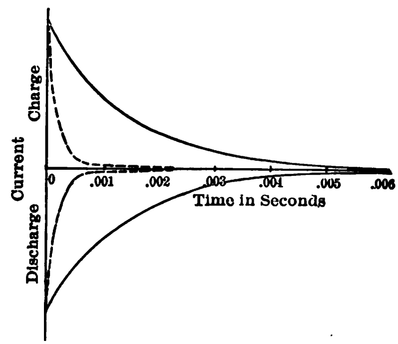



FIG. 130.—Charge and Discharge Curves of Condensers.

denser will be similar in shape but will be 90° ahead of the e.m.f. wave in phase; this is generally expressed by saying that a condenser draws a *leading current* from the line in contrast to an inductance, which draws a lagging current from the line. In Fig. 131 are shown three curves, one a sine wave of e.m.f., another the rate of change of this e.m.f., and in phase with this second curve is shown the current taken by the condenser. It is seen that this current wave is 90° ahead of the voltage wave.

*Power Used in a Condenser.* Now if the voltage and current in a circuit are 90° apart in phase the power used in the circuit must be zero, as power $=EI \cos \phi$ and $\cos 90°$

per second. Even a low voltage across this condenser would produce a very large charging current.

**54. Current in Circuits Containing Resistance, Inductance, and Capacity.** *Series Circuit.* Let us consider a circuit made up of an inductance, resistance and capacity all in series arranged as in Fig. 133.

Let $I$ = the current in the circuit;
$E$ = the voltage impressed on the circuit;
$R$ = the effective resistance of the circuit;
$L$ = the coefficient of self-induction in henries;
$C$ = the capacity of the condenser in farads;
$f$ = the frequency of the voltage.

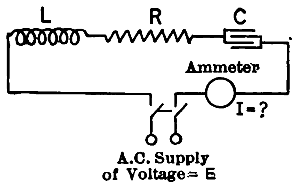



FIG. 133.—Circuit Containing Inductance, Resistance and Capacity in Series.

The three reactions which the current sets up in the circuit are:

Resistance reaction $= IR$, opposite in phase to the current;

Inductance reaction $= 2\pi fLI$, 90° behind the current;

Capacity reaction $= \dfrac{I}{2\pi fC}$, 90° ahead of the current.

The sum of these three reactions must be equal and opposite to the impressed force, $E$. The three reactions are plotted in Fig. 134 as $OB$, $OC$, and $OA$ respectively and their resultant is found to be $OE$. The impressed

opposite to $E$ in phase is shown the reaction of the condenser which is equal to $\frac{I}{2\pi fC}$. It is noticed that the *reaction* in a condenser *leads* the current by 90°; but with respect to the *impressed force* it is the current which leads.

*Ordinary Unit of Capacity.* The farad is too large a unit to be useful for ordinary condensers; their capacity is generally given in **microfarads,** the microfarad being one-millionth part of a farad. Condensers are used extensively in telephone service. The capacities used in different parts of the system range from one-tenth to a few microfarads. Condensers are also used largely in wireless telegraphy, but the capacities employed are very small, being only a small fraction of a microfarad for small outfits, and about one microfarad for very high-powered stations.

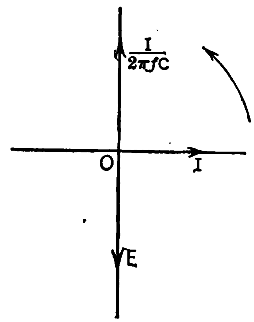


FIG. 132.—Vector Diagram of Condenser Reaction.

From the equation,

$$I = 2\pi fCE,$$

it is seen that, for a given voltage, the current increases directly with the frequency. For instance, a 10-microfarad condenser, on which is impressed an e.m.f. of 100 volts and 60 cycles frequency will have a charging current of $2\pi \times 60 \times 10 \times 10^{-6} \times 100 = 0.377$ ampere. If the frequency is increased to 1000 cycles, the current will be 6.28 amperes. In wireless telegraphy the frequencies used are very high and, therefore, large currents are obtained with small condensers. One of the transatlantic outfits has a capacity of 1.16 *microfarads and* is used on a circuit of 75000 cycles

It may be seen from Fig. 134 that $\tan\phi = EB/OB$ or

$$\tan\phi = \frac{2\pi fL - \dfrac{1}{2\pi fC}}{R} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (57)$$

or

$$\cos\phi = \frac{OB}{OE} = \frac{R}{\sqrt{R^2 + \left(2\pi fL - \dfrac{1}{2\pi fC}\right)^2}} \quad . \quad . \quad . \quad (58)$$

The term $\sqrt{R^2 + \left(2\pi fL - \dfrac{1}{2\pi fC}\right)^2}$ is called the **impedance** of the circuit and the term $\left(2\pi fL - \dfrac{1}{2\pi fC}\right)$ is called the **reactance** of the circuit. The letter $Z$ is used for impedance and the letter $X$ for reactance. Equation (56) would then be written,

$$I = \frac{E}{\sqrt{R^2 + X^2}} = \frac{E}{Z}; \quad . \quad . \quad . \quad . \quad . \quad (59)$$

and

$$\cos\phi = \frac{R}{Z}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (60)$$

or

$$\tan\phi = \frac{R}{X} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (61)$$

From these formulas any series circuit can be calculated. In case the circuit contains only capacity and resistance the current would be obtained by using equation 56 and putting $L = 0$. If there is neither inductance nor capacity in the circuit, equation 56 reduces to the well known Ohm's law $I = E/R$.

*Problem.* Suppose that we have an inductance of 0.01 henry and 50 ohms resistance in series with a capacity of 40 microfarads on a 60-cycle, 110-volt circuit. How much current will flow and what will be the power factor of the circuit?

$$I=\frac{110}{\sqrt{50^2+\left(2\pi 60\times 0.01-\frac{1}{2\pi 60\times 40\times 10^{-6}}\right)^2}}$$

$$=\frac{110}{\sqrt{50^2+(37.7-66.4)^2}}=\frac{110}{\sqrt{50^2+(-28.7)^2}}$$

$$=\frac{110}{57.6}=1.73 \text{ amperes.}$$

$$\tan\phi=\frac{-28.7}{50}=-0.575;$$

$$\phi=29^\circ\ 55' \text{ (leading current);}$$

or

$$\cos\phi=\frac{50}{57.6}=0.870 \quad \text{or} \quad \phi=29^\circ\ 55'.$$

*Parallel Circuits.* When there are two paths in parallel for the current to flow through, the calculation of the current becomes more difficult. It is generally easier to solve parallel circuits by the *vector addition* of the currents in the different branches. Suppose a circuit as given in Fig. 135. The magnitude and phase of the current in each branch is first determined and plotted on cross-section paper as in Fig. 136. The current in the inductive path is calculated to be $OI_1$, lagging behind the voltage $OE$ by the angle $\phi_1$. The current in the capacity branch is $OI_2$, leading the impressed force by the angle $\phi_2$. Now the line current must be the vector sum of the two branch

currents and is shown in Fig. 136 by $OI$ which lags behind the impressed e.m.f., $OE$, by the angle $\phi$.

It is evident that $OI$ may be considered as made up of two components, $OA$ and $AI$. These two components may easily be obtained from the branch currents by observing that

$$OA = OI_1 \cos \phi_1 + OI_2 \cos \phi_2,$$

and

$$AI = OI_1 \sin \phi_1 - OI_2 \sin \phi_2.$$

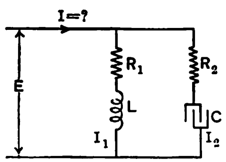



FIG. 135.—Inductance and Capacity in Parallel.

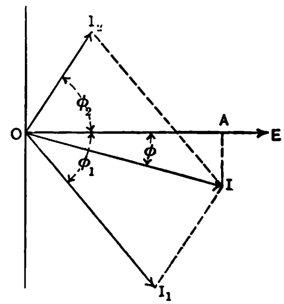



FIG. 136.—Current in the Circuit Shown in Fig. 135.

There is also another method for solving parallel circuits by a scheme involving the use of complex quantities but it is not thought desirable to introduce it in this elementary text.

**55. Resonance.** In circuits containing inductance and capacity, these two quantities may be so proportioned that

$$2\pi f L = \frac{1}{2\pi f C}. \quad \ldots \ldots \quad (62)$$

In such a case the inductance reaction becomes just equal to the capacity reaction and hence these two reactions will just neutralize each other, as they are opposite in phase.

The only reaction left to balance the impressed force is the resistance reaction and this may require a very large current. If an inductance, capacity and resistance are in series and $L$ and $C$ are so related that

$$2\pi fL=\frac{1}{2\pi fC},$$

then

$$I=\frac{E}{\sqrt{R^2+\left(2\pi fL-\frac{1}{2\pi fC}\right)^2}}=\frac{E}{R}.$$

The drop across the inductance (equal to $2\pi fLI$) may be very large because $I$ may be large. The same condition holds with respect to the condenser.

*Condition for Resonance.* When the frequency, inductance and capacity of a circuit are so proportioned that $2\pi fL=\frac{1}{2f\pi C}$, the circuit is said to be in a condition of **resonance**; the circuit is resonant. This condition obtains when $4\pi^2f^2LC=1$ or

$$f=\frac{1}{2\pi\sqrt{LC}}. \qquad (63)$$

The value of $f$ obtained by solving this equation for any circuit is said to be the *critical or resonant frequency* for the circuit.

*Example of a Resonant Circuit.* Suppose we have an inductance of 0.1 henry, a capacity of 70.4 micro farads and a resistance of 2 ohms connected in series to a 60-cycle, 110-volt line. How much current will flow and what will be the voltage across each part of the circuit?

$$I=\frac{110}{\sqrt{2^2+(37.7-37.7)^2}}=55 \text{ amperes.}$$

The drop across the inductance

$$= 2\pi f L I = 37.7 \times 0.1 \times 55 = 2073 \text{ volts.}$$

Across the condenser

$$\frac{55}{377 \times 70.4 \times 10^{-6}} = 2073 \text{ volts.}$$

Across the resistance

$$55 \times 2 = 110 \text{ volts.}$$

*Danger of the Resonant Condition.* Thus it is seen that in a resonant circuit having a low resistance *enormous voltages may build up across parts of the circuit;* the voltage across one part of the circuit may be many times greater than the voltage impressed on the whole circuit.

This condition of resonance does not occur very frequently in practice as the frequencies in common use are too low to give resonant circuits with ordinary inductances and capacities. It does, however, sometimes occur and then line insulators, transformer windings, etc. are broken down due to the high voltages set up in different parts of the circuit.

# CHAPTER VII

## THE ALTERNATING CURRENT GENERATOR

**56. General Construction.** The alternating current generator, or **alternator,** as it is frequently called, consists of a field structure, magnetized by electro-magnets, and an armature, in the winding of which the electromotive force is generated. In three respects the alternator differs greatly from the continuous current generator; it has no commutator, the field structure rotates instead of the armature as in the case of c-c. machines and an alternator is practically never self-exciting. Small alternators sometimes have a stationary field and a rotating armature, but all large alternators are of the revolving field type.

*Slip Rings Instead of Commutator.* In case the armature rotates the ends of its winding are connected to **slip rings** instead of to a commutator; the number of rings used depends upon the type of armature winding but generally there are either two or three. Brushes (generally made of blocks of some special metal) bear on these rings and serve to carry the current to the external circuit. When the field revolves, the continuous current for its excitation is led into the field winding by means of slip rings and brushes.

*Alternator Not Self-exciting.* The current for the field winding must be continuous and as the armature of the alternator furnishes only alternating current it is evident that some additional source of power must be available for obtaining the field excitation.

*Reasons for a Stationary Armature.* There are several reasons why the field of an alternator generally rotates instead of the armature. The armature winding ordinarily generates quite a high voltage, perhaps 2300 volts or even 11,000 volts. Such voltages require that the armature winding be very carefully insulated and it is much easier to insulate a stationary winding than it is to insulate one designed to run at a high speed. In the latter case the winding has to be designed to stand properly the mechanical stresses due to centrifugal forces and, as a result, the insulation is likely to be inferior.

As the armature of an alternator is not equipped with a commutator, it is not at all necessary to have the armature rotate and so they are nearly always stationary.

*Special Field Structure for Turbo-alternators.* The steam turbine is used very often as the driver for alternators and a turbine must necessarily run at high speed to use the steam economically. Now the field of an alternator can be designed to stand the mechanical stresses due to this high rotative speed much better than the armature can. The field structure may be made of blocks of machine steel, while an armature must be made of laminated iron; also the field winding requires but very little insulation, while the winding of an ordinary armature demands insulation perhaps one-eighth of an inch or more in thickness. This amount of insulation makes the armature mechanically weak and unable to stand high speeds of rotation.

*Typical Forms of Alternators.* Fig. 137 shows a small alternator having a rotating armature, with slip rings, etc., and Fig. 6 shows a revolving-field alternator which generates 2300 volts and is for use in a large a-c. power plant. The field structure is very strongly made and the coils are strap wound as described on page 72 and shown in Fig. 37. The multi-polar machine illustrated in Fig. 6 was designed to be run at a low speed by a reciprocating engine. Alternators designed for turbine drive are much

more compactly designed and have but few poles, generally two or four.

**57. Frequency.** Alternators have been designed for many different frequencies, but the standardization of electrical apparatus has eliminated all but two, so that all

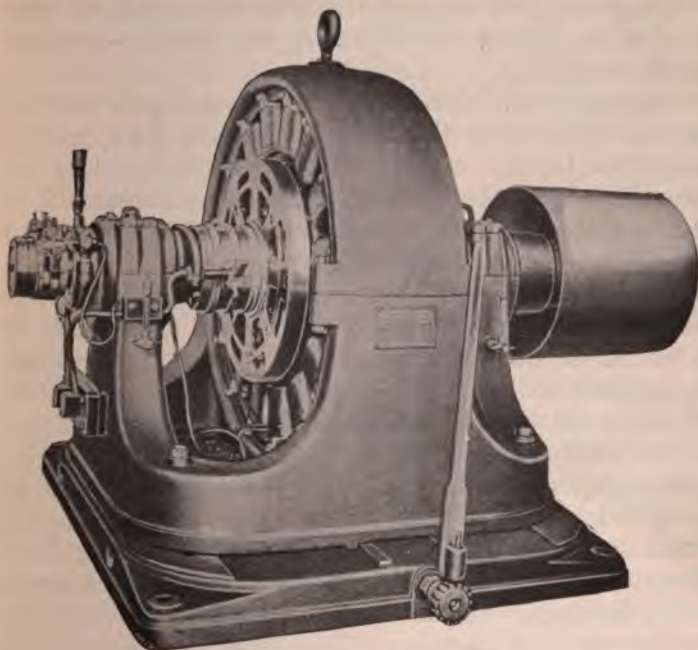


FIG. 137.—Small Alternator Having Rotating Armature, Fitted with Slip Rings. This is an early type of alternator.

modern machines are designed for either 60 cycles or 25 cycles per second. Earlier machines were built to give 133 cycles per second and there has been much talk of machines for 15 cycles but the two named above are the only standard frequencies used in American practice. In Europe other frequencies are much used.

*Frequency Fixed by the Speed and the Number of Poles.* The frequency of the e.m.f. which an alternator generates depends upon its *speed and upon the number of poles.* A complete cycle is generated in any conductor on the armature when a pair of poles have moved past it, *hence to find the frequency of an alternator it is only necessary to calculate the number of pairs of poles passing any armature conductor in one second.*

*Typical Cases.* Take, for example, a four-pole machine turning 1800 r.p.m.; there are two pairs of poles, so that every time the field makes a complete revolution there are two cycles generated in any armature conductor. Now this machine is turning 30 rev. per sec. and hence the frequency is equal to $30\times2=60$ cycles per second. Suppose a 10-pole machine turns 300 r.p.m.; it generates 5 cycles per revolution and makes 5 rev. per sec., therefore it generates a frequency of $5\times5=25$ cycles per second. A certain turbo-alternator has two poles and turns 1500 r.p.m.; it generates therefore 25 cycles per second.

**58. Excitation.** Attempts have been made to build self-exciting alternators but they have been failures as evidenced by the fact that there are practically none in service, except an occasional machine of very small capacity. These small alternators with self excitation are sometimes called double current generators.

*Separate Excitation from Small C-C. Machines.* All alternating current stations have two or more small, self-exciting, shunt-wound (or compound-wound), continuous current machines whose sole purpose is to furnish the field current for the alternators. As the amount of power used in the field coils of an alternator is generally less than 5% of its capacity, the exciters may be comparatively small machines. An alternator having a capacity of 1000 kw., for example, would require an exciter of about 25 kw. capacity.

*Arrangement of Exciters in a Station.* Sometimes each alternator is furnished with its own exciter (either belted

or direct-connected), but in large stations there is generally a set of exciter bus bars on the switchboard and two or more exciters (each equipped with its own driver) furnish power to these busses. The field circuit of all alternators are connected to this set of exciter bus bars. The exciters are sometimes driven by alternating current motors and at other times by small steam turbines or engines.

The field winding of an alternator is generally designed for 125 volts and this is, of course, independent of the voltage generated in the armature winding, which may be several thousand volts.

**59. Armature Winding.** In general, the armature winding of an alternator resembles that of a continuous current machine but is much simpler; it has comparatively few coils and they are generally connected all in series. It was shown in Chapter II that the winding of a c-c. armature might be rather complex, using fractional pitch and being either of the wave or lap type. But no such complexities are encountered in alternator armatures; there are generally not more than six coils per pair of poles and seldom more than twelve and the arrangement and connections of these coils are very simple. In the continuous current armature it was necessary to use many coils of few turns each in order to have the commutation take place without sparking, but the alternator has no commutator and therefore this limitation on its winding does not exist.

*Single-phase and Polyphase Winding.* Sometimes all the coils on an armature are connected in series with one another so that there is only one set of coils on the armature; this is said to be a *single-phase* winding and the machine is called a **single-phase generator.** There are only two ends to the armature winding so the machine has but two slip-rings and two brushes. Sometimes the coils of the armature are divided in a certain way, to form two equal independent groups and this is called a **two-phase winding.** More often the coils are divided into three equal groups

and form a **three-pnase winding.** Probably ninety-five per cent of the alternators in use to-day are three phase machines. The two-phase winding sometimes employs four slip-rings and sometimes three; the three-phase winding always has three slip-rings.

*Development of the Different Types of Winding.* The development of these three styles of winding and the meaning of the names will now be taken up. Suppose an elementary generator, having only one coil and two slip-rings, as shown in Fig. 138. The e.m.f. wave which such an armature would generate is shown in Fig. 138. It is a simple sine wave.

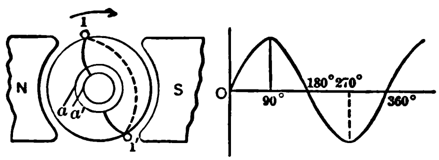



FIG. 138.—E.M.F. Wave Form of Single-phase Generator.

Now suppose another coil is wound on the same armature, insulated from the first coil and connected to two more slip-rings. This armature is shown in Fig. 139; the four rings are shown one outside the other, whereas really they would be all of the same size placed by the side of each other on the armature shaft.

*The e.m.f. generated by coil 2–2′ will evidently be of the same shape and magnitude as that generated by coil 1–1′, but its maximum value will occur 90 electrical degrees later in time than the maximum value of that generated in coil 1–1′.* The e.m.f. waves of the two coils are shown in Fig. 146, that of coil 1–1′ being given by the full-line curve and that of coil 2–2′ by the dotted curve.

This armature would, therefore, feed power to two separate circuits, one connected to the brushes *a–a′* and the other to the brushes b–b′. The e.m.fs. on these two

circuits would be equal in magnitude, but the phase of one would be 90° behind that of the other. The generator is said to be a **two-phase generator** and the two circuits to which it supplies two-phase power is called a **two-phase system.**

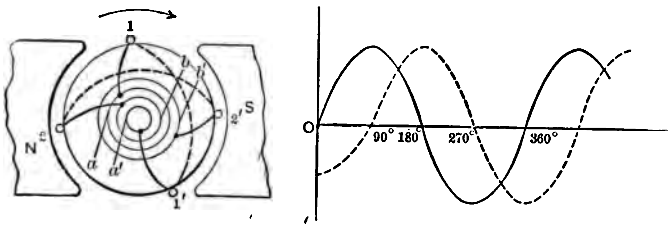



**Fig. 139.**—E.M.F. Wave Forms of a Two-phase Generator.

Sometimes the beginnings of the two coils are connected together inside the armature winding; this connection is brought out to one slip-ring and the two ends are connected to two other rings. Such a machine is called a *two-phase, three-wire* alternator, as contrasted to that

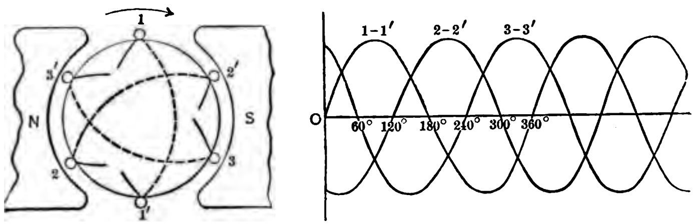



**Fig. 140.**—E.M.F. Wave Forms of a Three-phase Generator.

shown in Fig. 139, which is a *two-phase, four-wire* alternator.

Now instead of placing two coils on the armature, 90° apart, we might place on it three coils 120° apart as shown, in Fig. 140. The three e.m.f. waves generated by such a winding would all be of the same magnitude but would

differ in phase from each other by 120°; this winding is called a **three-phase winding,** and the system of wires to which such an armature supplies power is called a **three-phase system.**

It might seem that a three-phase system must consist of *six wires;* as a matter of fact, there are never more than *three wires.* The coils are always so inter-connected in the armature that only three slip-rings are required on the armature and hence only three wires in the three-phase distributing system.

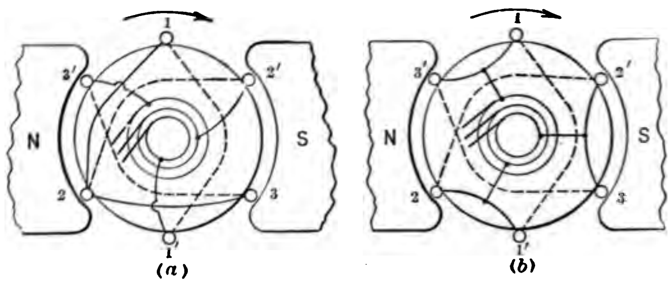



FIG. 141.—Two Ways of Interconnecting the Coils of a Three-phase Armature.

*Three-phase Y-connection.* There are two ways of making this inter-connection of the coils; sometimes one is used and sometimes the other, but in either case only three rings are used on the armature and only three wires are used in the outside circuit. Fig. 141 (*a*) and (*b*) show the two methods of connecting a three-phase armature. In (*a*) all of the beginnings of the coils are connected together and the ends of the coils are connected to the three slip-rings. The junction of the beginnings of the coils is not connected to any ring. An armature so connected is said to be **Y-connected** because a schematic diagram of the winding resembles the capital letter Y,

*Three-phase Δ-connection.* The other method of connecting the coils is called the **delta connection,** so named because its schematic diagram resembles the Greek letter Δ. In this connection the end of coil 1 is connected to the beginning of coil 2, the end of coil 2, connected to the beginning of coil 3, and the end of coil 3 is connected to the beginning of coil 1. Then the three junction points are connected to the three slip-rings, as shown in diagram (*b*) of Fig. 141. The Δ-connection is not used as frequently as the Y-connection.

*Equality of Voltages in a Three-phase System.* The three-phase system is peculiar in that *the voltage measured between any pair of wires is the same,* and this is true no matter whether the generator armature is Δ or Y-connected. Having a given three-phase winding on an armature, the output capacity will be just the same whether the Δ or Y connection is employed, but the Y-connected machine will give a higher voltage between lines than the Δ-connected machine. The possible current output of the latter machine is greater than that of the Y-connected machine in the same ratio as its voltage is smaller, so that the two outputs are equal.

A discussion of the voltage and current relations and of the power and power measurement of three-phase circuits will be taken up in detail in Chapter XIV.

Of course the armature windings of an alternator are not arranged as shown in the simple diagram given in Figs. 138–141; there are generally several pairs of poles on an alternator and there is always more than one coil per pair of poles, per phase.

*A Typical Armature, to be Connected in Various Ways.* Let us consider a four-pole alternator having twenty-four slots on the armature, so that there are six slots per pole. The first thing to note about the winding of an a-c. armature is that *there is generally only one coil side placed in any one slot.* (This is different from the c-c. armature which

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Across the condenser

$$\frac{55}{377\times 70.4\times 10^{-6}}=2073 \text{ volts.}$$

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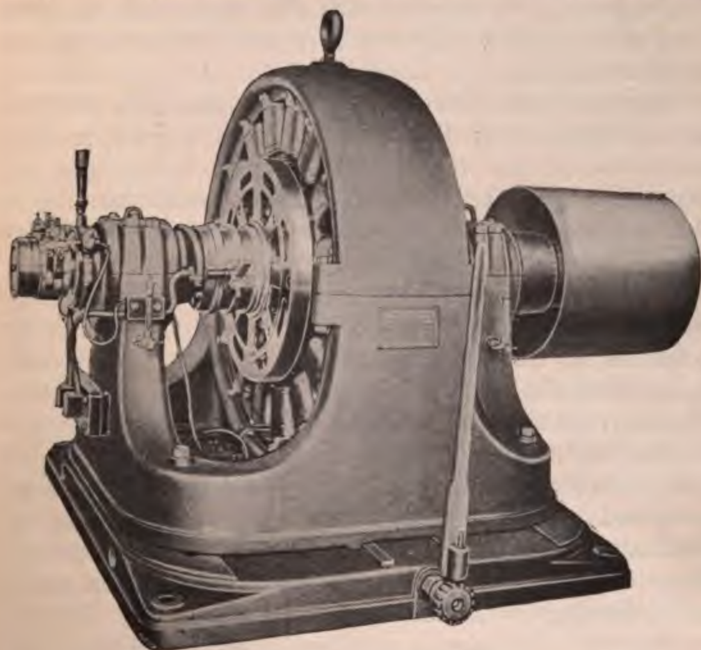

FIG. 137.—Small Alternator Having Rotating Armature, Fitted with Slip Rings. This is an early type of alternator.

modern machines are designed for either 60 cycles or 25 cycles per second. Earlier machines were built to give 133 cycles per second and there has been much talk of machines for 15 cycles but the two named above are the only standard frequencies used in American practice. In Europe other frequencies are much used.

*Proper Bracing for Armature Coils.* When the winding is for the armature of a slow speed, multiple-pole generator the end connections are short and rigid and require no extra bracing to prevent bending in case of excessive

Fig. 148.—Formed Coils for a Polyphase Winding Showing How End Connections are Bent to Lessen Liability of Insulation Break-down between Coils of Different Phases. Allis-Chalmers Co.

current in the armature winding. In the case of a turbo-generator, designed for high speed, and hence having a field frame of only two or four poles, the end connections *are very long;* if a short-circuit occurs on such a machine

or direct-connected), but in large stations there is generally a set of exciter bus bars on the switchboard and two or more exciters (each equipped with its own driver) furnish power to these busses. The field circuit of all alternators are connected to this set of exciter bus bars. The exciters are sometimes driven by alternating current motors and at other times by small steam turbines or engines.

The field winding of an alternator is generally designed for 125 volts and this is, of course, independent of the voltage generated in the armature winding, which may be several thousand volts.

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*Single-phase and Polyphase Winding.* Sometimes all the coils on an armature are connected in series with one another so that there is only one set of coils on the armature; this is said to be a *single-phase* winding and the machine is called a **single-phase generator.** There are only two ends to the armature winding so the machine has but two slip-rings and two brushes. Sometimes the coils of the armature are divided in a certain way, to form two equal independent groups and this is called a **two-phase winding.** More often the coils are divided into three equal groups

Fig. 149 shows the end connections of a four-pole turbo-generator; the long end connections are evident and some of the bracing may be seen. Such a machine, if it has insufficient bracing at the end connections, may have its coils so twisted and bent in case of a short-circuit that the whole winding is ruined.

**60. Armature Reaction.** *A-C. Machine compared to a C-C. Machine.* The study of armature reaction in alternators is more difficult than that of continuous current generators. The conductors of a continuous current machine carry a current of constant value during one-half a revolution (180 electrical degrees) and the current has the same value during the next half revolution but is reversed in direction. In Chapter III it was shown that this resulted in a constant magnetizing or demagnetizing effect, combined with a constant cross-magnetizing effect on the field.

Now the conductors of an alternating current armature carry a current which is continually varying, so that each coil by itself produces a periodic effect on the strength of the field. In the case of a single-phase machine the entire armature winding produces a pulsating effect on the main field, while in the case of a polyphase machine the instantaneous effects of all the separate coils so combine as to produce on the main field an effect which is constant in magnitude and direction, the same as the continuous current armature.

*Analysis of the Action of a Single-coil Alternator with a Non-inductive Load.* A fair idea of the action of a single-coil alternator may be obtained by studying Fig. 150. A two-pole machine is considered and it is supposed that the current in the coil is *in phase with the generated e.m.f.* so that the current is a maximum when the coil is in the axis of the main field. This position of the coil is numbered 4–4′ in Fig. 150. The m.m.f. of the coil is given by the vector $Od$, at right angles to the plane of the coil.

When the coil is in the position 1–1′ the current is zero

and hence there is no m.m.f. generated by the coil. At the position 2–2′ the current has started to build up and the m.m.f. generated by the coil is shown by the vector *Ob*, which is proportional to the value of the current when the coil is in the position 2–2′ and is at right angles to the coil in this position. The m.m.fs. for the other positions of the coil given in Fig. 150 are shown by *Oc*, *Oe* and *Of*.

*Locus of Armature M.M.F. is a Circle.* The vectors, if carefully constructed, are found to be on a circular locus, which locus is given in Fig. 150 by the dotted circle. As the armature continues to rotate (only 180° of rotation

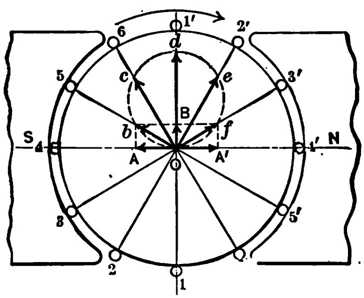



FIG. 150.—Locus of Armature Reaction of a Single-phase Generator, Current in Phase with Generated e.m.f.

is considered in Fig. 150) the m.m.f. vector of the armature starts again over this same circular locus.

*Division of Armature M.M.F. into Components.* If we consider any m.m.f. vector (as for example *Ob*), it is seen that this may be divided into two components, *OA* which tends to directly *magnetize* the main field, and *OB* which tends to cross-magnetize the main field. For every vector *Ob* there will be one symmetrically placed with respect to *Od* as an axis of symmetry. In the case of *Ob* the symmetrical vector is *Of*. This vector *Of* may be resolved into its two components, *OA′* and *OB*; the com-

ponent $OA'$ tends to directly *demagnetize* the main field and $OB$ is a cross-magnetizing effect.

Now every other vector has its mate and the resultant direct magnetizing or demagnetizing effect of any such pair is zero, because the magnetizing component of one is just equal to the demagnetizing component of the other. The cross-magnetizing effect of the two vectors ($Ob$ and $Of$ for example) is in the same direction so that the cross-magnetizing effect is not neutralized.

Hence we conclude that *in the single-phase alternator, the armature of which is carrying current in phase with its generated e.m.f., the armature reaction produces no resultant demagnetizing effect but does cross magnetize the main field so that it is concentrated in the trailing pole tips.*

*Armature M.M.F. Produces Pulsations in the Strength of the Main Field.* But although there is no net magnetizing effect in such a machine it is to be noticed that at some instants the main field is stronger than normal and at others, weaker (because of the magnetizing effect $OA$ and demagnetizing effect of $OA'$, for example). As a result the main field pulsates in strength, and a study of this effect shows that this pulsation takes place with a frequency just twice as great as that of the generated e.m.f. of the armature. It may also be seen that the cross-magnetizing action is also pulsating in its effect, being a maximum when the armature current is a maximum and 90° later, being zero.

*Effects of Single-phase Armature Reaction.* The total effect of the armature reaction in a single-phase generator carrying current in phase with its generated e.m.f., is, therefore, a periodic weakening and strengthening of the main field combined with a periodic oscillation of the field back and forth across the pole face. *Both of these effects produce eddy currents in the pole face* so that a single-phase generator, unless special precautions have been taken in the design, is likely to develop a great amount of heat in

the pole. In some cases this effect has been the factor that limited the output.

*Single-phase Armature Reaction with Inductive Load.* Suppose now that the single-phase generator is carrying an inductive load. The current in the armature will have the same m.m.f. locus as it had in Fig. 150, but this circular locus will be rotated toward the right as shown in Fig. 151. This represents the conditions for a lagging load of power factor $=.7(\phi=45°)$. It may be seen that the components $OA$ and $OA'$, of a pair of vectors, *no longer neutralize one another;* in fact with $\cos\phi=.7$ (Fig. 151),

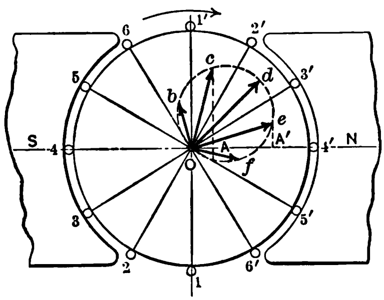



FIG. 151.—Locus of Armature Reaction of a Single-phase Generator, Lagging Current.

*both of these represent a demagnetizing action* on the main field. The sum of all the demagnetizing and magnetizing components shows *the net result to be a demagnetizing effect for a lagging load.* The cross-magnetizing effect is still present but not to such an extent as it was for $\cos\phi=1$, because during part of the alternation the cross-magnetizing effect pushes the *main field into the leading pole tips.* This would be the effect of the cross-magnetizing component of $Of$, for example.

The result of these combined actions is that the armature reaction of a single-phase generator, furnishing current to an inductive load, not only makes the main field pulsate

in strength and oscillate across the pole face, *but also produces a weakening of the main field*, the amount of weakening depending upon the magnitude of the current in the armature and upon the power factor of the load, and being greater the less the power factor.

*Single-phase Armature Reaction with Leading Armature Current.* In case the alternator is furnishing current to a load having a leading power factor, the locus of the armature m.m.f. is a circle but is rotated backward from the position it had for a non-inductive load. This condition is shown in Fig. 152. A study of this figure shows that

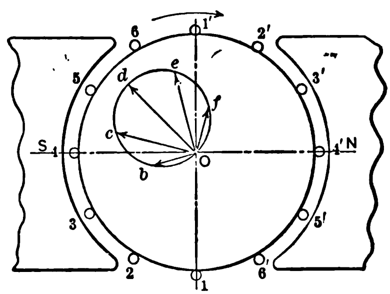



FIG. 152.—Locus of Armature Reaction of a Single-phase Generator, Leading Current.

for the single-phase alternator, furnishing a leading current, the armature reaction results in a periodic pulsation in the strength of the main field, an oscillation of the field across the pole face from the leading to the trailing pole tips and back, *and a strengthening of the main field*, which is proportional to the armature current and dependent upon the power factor, being greater the less the power factor.

*Reaction of an Actual Multiple-coil Winding.* The previous analysis has been carried out for an armature having a single coil; however, any ordinary single-phase winding produces an effect nearly the same as though the armature had but one turn, there being such a current

in this one turn that the ampere-turns on the armature are the same as with the real winding.

*Magnitude of the Effect of Armature Reaction Upon the Main Field.* The magnitude of the effect of the armature reaction depends upon the ratio of the armature ampere-turns to the field ampere-turns. A machine having many ampere-turns on its field (thus saturating the field poles) and but few ampere-turns on its armature is said to have *a stiff field.* The field of such a machine is affected but little by armature reaction.

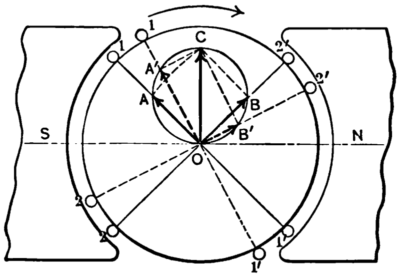
*Analysis of Armature Reaction in a Two-phase Alternator with Non-inductive Load.* The effect of armature reaction in a polyphase generator may easily be obtained by drawing the vector showing the armature m.m.f. for each phase separately and then combining them. Thus in the two-phase armature the total m.m.f. may be obtained by adding vectorially two chords of the circular locus at right angles to one another. They are added at right angles because the phase windings on the machine are 90° apart.

*Reaction Constant in a Two-phase Alternator.* Fig. 153 shows that the m.m.f. of the armature resulting from such a construction *is constant in magnitude and direction.* The m.m.f. of phase 1–1′ is shown at *OB* and at the same instant phase 2–2′ is producing the m.m.f. *OA*. The resultant of these is *OC*, and *no matter at what instant the armature reaction is considered the resultant will always be OC, the maximum value of the m.m.f. of one phase.*

*Reaction with Inductive Load.* Fig. 153 shows the conditions for a non-inductive load. The resultant *OC*, is seen to be entirely a cross-magnetizing effect. Now if the load were inductive the proper diagram would show that the armature reaction is of the same magnitude *OC*, but that it is advanced in the direction of rotation, as *OC* of Fig. 154; the angle of advance being equal to $\phi$, where $\cos \phi$ is the power factor of the load.

Now in the case of a load with a leading current the

armature m.m.f. would still be of a magnitude equal to $OC$ but its direction would be behind that of $OC$, as shown at $OC'$, of Fig. 154. Again the angle $YOC'$ is equal to $\phi$.




Coils and vectors in dotted lines show conditions for a fraction of a revolution later than those shown by full lines.

FIG. 153.—Armature Reaction in Two-phase Alternator, Current in Phase with Generated e.m.f.

*Reaction of a Three-phase Alternator.* The student may construct for himself the diagram for a three-phase alternator, and will find that this machine, like the two-

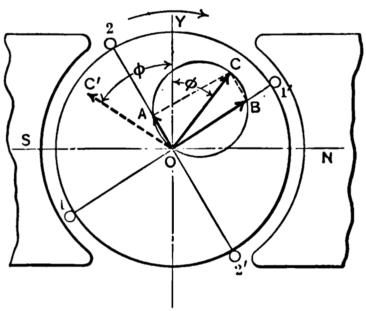



FIG. 154.—Armature Reaction in Two-phase Alternator, Lagging and Leading Current.

phase machine, gives a non-pulsating armature reaction. The magnitude of the reaction depends upon the magnitude of the armature current and is equal to 1.5 multiplied by

the magnitude of the maximum reaction of one phase of the winding. The direction of this reaction depends upon the power factor of the load, a lagging load demagnetizing the field and a leading one magnetizing it.

*Previous Analyses for Balanced Loads Only.* The previous analyses have been carried out on the assumption of a balanced polyphase load, i.e. all phases carrying currents of the same magnitude. Summing up the results for a polyphase machine, we see that, when the load is balanced, *the armature reaction is constant in magnitude and direction, the same as in a continuous current machine; the magnitude of the reaction depends upon the value of the armature current and the direction depends upon the power factor of the load.*

**61. Rating of A-C. Machinery.** The rating of alternating current machines, generators, transformers, etc. is practically never given in kilowatts but in kilovolt-amperes. A generator having a safe current capacity of 10 amperes and giving an e.m.f. of 100 volts would be rated as having a capacity of one kilovolt-ampere or abbreviated, 1 kv-a.

To get the rating of a single-phase generator or transformer the safe capacity in amperes is multiplied by the terminal voltage and this product is divided by one thousand. For example a 2300-volt alternator having a safe current capacity of 100 amps. would have a rating of $\frac{2300\times 100}{1000}$ $=230$ kv-a.

*Capacity of Polyphase Machines.* If it were a two-phase alternator having a capacity of 100 amperes per phase and giving 2300 volts in each phase, the kv-a. rating would be twice that of one phase, or 460 kv-a. If it were a three-phase alternator, giving 2300 volts between any two lines and having a capacity of 100 amperes per line the kv-a. rating would be equal to $\frac{2300\times 100\times\sqrt{3}}{1000}=398$ kv-a.

From this example it is seen that the kv-a. capacity of a three-phase machine is obtained by multiplying the product of the safe current per line times the voltage between lines by $\sqrt{3}$ and dividing by 1000. The reason for the use of $\sqrt{3}$ in this calculation will be given in Chapter XIV.

*Reason for Rating in Kilovolt-amperes.* Why should the capacity of an alternating current machine be given in kilovolt-amperes instead of in kilowatts? We have shown that the output of an electric machine is fixed by the safe heating and that this heating in the conductors fixes, therefore, the safe current the machine may carry. Its voltage is fixed by the saturation of the magnetic field, number of conductors, speed, etc. and cannot safely exceed that for which the machine was designed. *The two limiting factors of the output are thus the current and voltage,* and it may be that the power factor of the load to which the generator is furnishing current is less than unity.

*Example.* Let us consider the 2300-volt, 100-ampere, single-phase generator; its rating was 230 kv-a. Now if the load power factor were 0.5, when the machine was delivering 100 amperes at 2300 volts the watts output would be $2300 \times 100 \times 0.5 = 115000$ watts $= 115$ kw. So that the generator would be working to its safe limit to supply 115 kw., whereas if the power factor of the load were unity the possible output would be 230 kw. Thus the possible power output of a generator depends entirely upon the power factor of the load; alternating current machinery is therefore rated in terms of volts and amperes, and not watts. If a machine should be rated in kilowatts a load of power factor equal to unity would be assumed.

**62. Characteristic Curves.** The two curves to be considered here are the external characteristic and armature characteristic. The latter is often called the field-compounding curve. The efficiency curve is similar in shape to that of a continuous current generator and, as the same factors determine the form of the curve for both machines, they

will not be taken up here. They were discussed and analyzed in Chapter V in detail.

*External Characteristic.* The external characteristic of an alternator shows the relation between the terminal voltage and the load current, the field current being held constant at that value which gives rated voltage when rated full-load current is being carried. The shape of this curve resembles that of a continuous current, separately-excited generator but the shape of the curve for an alternator depends somewhat on the power factor of its load. Fig.

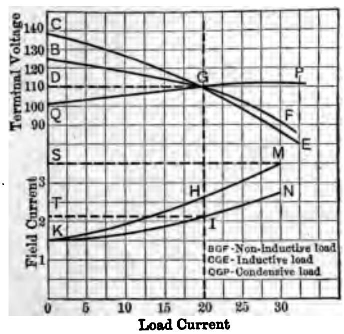



FIG. 155.—External Characteristics of an Alternator on Different Loads.

155 serves to illustrate this point; the rated full-load voltage is *OD* and the external characteristic for a non-inductive load is shown by the curve *BGF*, for an inductive load by the curve *CGE*, and for load of leading power factor by the curve *QGP*. It will be noticed that the drop in terminal voltage, for a given increase in load current, is greater for an inductive than for a non-inductive load.

*Short-circuit Current.* The value the current reaches when the resistance in the load circuit is reduced to zero (called *the short-circuit current*) may be from three to ten times the rated full-load current, depending upon the

design of the machine; ordinarily it is about five times the rated full-load current.

If the armature impedance is known of course the short-circuit current can be approximately calculated. The *generated voltage* of a certain machine is 122 volts when the machine is excited to give its rated voltage, 110 volts, when carrying the full-load current of 50 amperes. The armature impedance is measured and found to be .40 ohm. Now if the external circuit resistance is reduced to zero (i.e., the machine is short circuited) all of the generated voltage must be used up in *overcoming the impedance drop in the armature.* So that we may put

$$E=IZ;$$

or

$$110=I\times .40$$

from which

$$I=275 \text{ amperes.}$$

The short-circuit current of this machine is, therefore, five and one-half times the full-load, rated current.

*Factors Affecting the Form of the External Characteristic.* The factors which act to change the terminal voltage of an alternator as the load is varied are: the armature resistance, the armature inductance, and the armature reaction. In obtaining the external characteristic the field current is maintained constant and hence, if the armature current did not affect the field strength, the generated e.m.f. would remain constant as the load varied. But, as previously shown, the armature reacts to affect the strength of the main field; a lagging current demagnetizing the field and a leading current magnetizing the field. Thus, as a lagging load is increased, the *generated e.m.f. of the armature decreases* even though the field current and speed are held constant. With a load of leading current, the *generator e.m.f. increases with an increase* of load.

The terminal voltage is obtained by subtracting (vectorially) the armature $IR$ and $IX$ drops from the generated e.m.f. These combined effects give external characteristics similar in form to those given in Fig. 155.

*Field Compounding Curve.* The armature characteristic, or field compounding curve, shows the relation between the load current and the field current, the latter being so varied that the terminal voltage of the alternator remains constant as the load is changed. The field current must be increased to a considerable extent when the load is changed from zero to rated capacity and over and this increase is greater for an inductve than for a non-inductive load.

Experimentally obtained results for a small alternator are given by the curves $KIN$ and $KHM$ of Fig. 155. The first curve is for a non-inductive load and the second for a load of $\cos \phi = .7$, lagging current.

*Capacity of the Exciter.* The exciter for this alternator must be designed to carry safely the current required under the worst condition, i.e., overload with a lagging current. Thus the exciter for the alternator whose curves are given in Fig. 155 should be designed to carry the current $OS$, although with a normal non-inductive full-load current, the required field current is only $OT$.

**63. The Voltage Regulator.** Commercial loads always have a lagging current and so if the excitation of an alternator were left unaltered as the load increased, the terminal voltage would fall to a considerable extent. It is desirable with most pieces of apparatus to which power is supplied (lamps, motors, transformers, etc.), to maintain a constant voltage at the *piece of apparatus.*

This necessitates an *increase* in the terminal voltage of the generator supplying the power, to overcome the increased line drop with increased load, but if left to itself the alternator would give a *decrease* in terminal voltage. Hence it is necessary either to have the operator vary the

alternator field current as the load is increased and decreased or else to have some automatic device to regulate the alternator field.

*Operation of the Voltage (or Tirrill) Regulator.* The Tirrill regulator (so named after its inventor) serves the purpose by controlling a resistance in the field of the exciter furnishing the alternator field current. A cut showing this ingenious device is given in Fig. 156 and

Fig. 156.—View of Voltage Regulator (Tirrill Regulator) General Electric Co.

a diagram of its connections is given in Fig. 157 by reference to which its action will be described. A diagram of the exciter with its field rheostat and its connection to the alternator is given to make the operation of the regulator easier to understand.

Essentially the regulator consists of three magnets, $A$, $A'$, and $F$ and two pairs of contacts $C$, $C'$ and $E$, $E'$, which are opened and closed by these magnets.

*Differential Relay Magnet.* The operation of the *differential relay* magnet $F$ will first be described. Its winding

consists of two coils, *H* and *H'*, both of which are excited from the terminals of the exciter. One of them, *H*, is excited all the time the exciter is running while the other *H'* is excited only when the two contact points *C* and *C'* make connection with each other. These two coils are differentially wound, so that, when both of them are excited, there is no pull on the armature *S* and the relay contacts *E* and

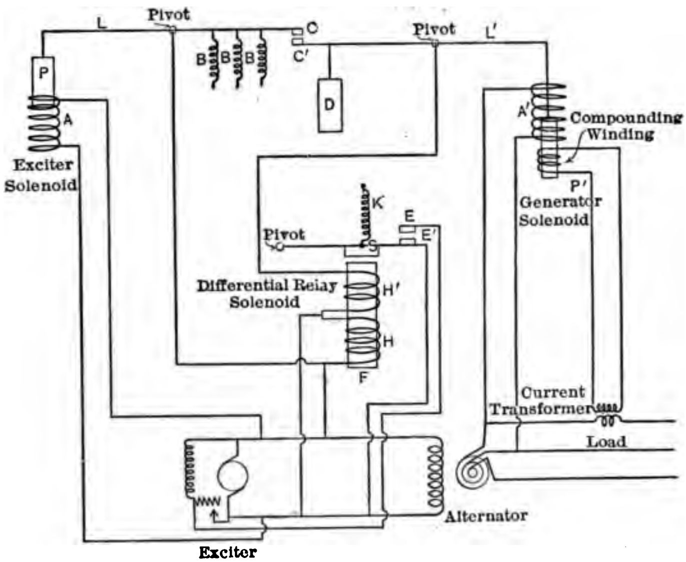



FIG. 157.—Connection Diagram of Voltage Regulator.

*E'* remain closed by the action of the spring *K*, but when contacts *C* and *C'* are opened so that only coil *H* is excited the solenoid *F* is magnetized, the armature *S* is pulled down, and the contacts *E* and *E'* are separated.

The contacts *E*, *E'* are connected to the field rheostat of the exciter, *so that when they are together the rheostat is short-circuited but when they are apart the rheostat is in the field circuit* as it is ordinarily. Hence, when *C* and *C'* touch

each other, the exciter voltage rises (due to cutting out the field rheostat) and when they separate the exciter voltage falls. When the regulator is in operation, the armature $S$ is continually vibrating (due to actions described later) so that the exciter voltage is continually oscillating above and below its proper normal value.

*Action of the Exciter Solenoid.* Suppose now that contact $C'$ remains in a fixed position; we will examine the action of the solenoid $A$, which is connected across the exciter terminals. The plunger $P$ is carried on a lever, $L$, and is held in its highest position, when $A$ is not excited, by the spring $B$. The magnetic pull of $A$ is about equal to that of the spring $B$. As the exciter voltage *rises and falls* therefore, the plunger $P$, *falls and rises* accordingly and so the contacts $C$ and $C'$ are correspondingly opened and closed.

*Combined Action of Relay Magnet and Exciter Magnet.* We have seen that the operation of the contacts $E$, $E'$ is effected by the opening and closing of the contacts $C, C'$. Hence the combined action of the relay magnet and exciter magnet is to maintain the exciter voltage constant (and hence maintain the generator field current constant). For suppose (after the regulation has been properly adjusted) that the exciter voltage rises above normal. The plunger $P$ is pulled down opening the contacts $C$, $C'$, thus (by the action of the relay magnet) opening the contacts $E$, $E'$. This inserts the rheostat in the exciter field, by opening the short-circuit path in parallel with the rheostat.

This action will decrease the field current of the exciter, and therefore will decrease its voltage. The magnetic pull on the plunger $P$ is thus lessened, and it rises due to the action of the spring $B$. This closes the contacts $C$, $C'$, closing the contacts $E$, $E'$ and so short-circuiting the field rheostat once more. The exciter voltage again rises and the process is repeated. This action keeps the armature

$S$ in continual vibration at a rate of several vibrations per second.

*Action of the Generator Solenoid.* Now consider the action of the generator solenoid $A'$. Its winding is connected across the terminals of the generator (through a potential transformer for high-voltage machines) and the action of its magnetic pull is to *raise plunger* $P'$. The plunger $P'$ is suspended from a lever $L'$ and counterbalanced to any desired degree by the adjustable weight $D$. When the regulator is in adjustment and the voltage of the generator is normal, $P'$ (and hence $C'$ which is carried on the same lever as $P'$) occupies a certain mean position. Voltage on the alternator above normal will lift $P'$ above its normal position and so depress $C'$ below its normal position. A decrease in alternator voltage will have the opposite effects.

But if $C'$ is lowered it will require less pull on $P$ to make the contacts $C$, $C'$ open, so they will open on less than normal exciter voltage, and when they open the exciter voltage falls as explained before. But if the exciter voltage falls, a corresponding decrease in the alternator voltage must occur. Hence the total action of the regulator is to bring the alternator voltage back to normal if it tends to rise; also if the alternator voltage falls an increase in the exciter voltage (and hence in the alternator voltage) must take place.

The Tirrill regulator has been so perfected that it is possible by its use to maintain the voltage of an alternator *constant to within one-quarter of one per cent.*

*The Regulator may be used to Compound an Alternator.* It is many times desired to have the alternator voltage *increase with the load* so as to overcome the line drop and give constant voltage at some distant point on the line. This is easily done by winding on $A'$ another coil and connecting it to a current transformer in the generator line, the connection to be so made that the action of this second

winding is to neutralize the other. By properly proportioning this second differential winding it is possible to obtain any degree of compounding desired.

There are several auxiliary features to the regulator which we have not considered, such as condensers across the contacts, reversing switches for the contacts, the amount of resistance required in the field rheostat for proper operation, etc. These may be found in trade publications describing the regulator.

**64. Alternators Running in Parallel.** Electrical power for a city or community can be generated most efficiently when all the generators supplying the power are located in one central power station. The cost of electrical power may be divided into several parts; coal and water, oil, station attendance and repairs, line maintenance, interest on investment and various other costs grouped under the title of "overhead" charges. These are made up of office rent, salaries of clerks, executive officers, taxes, etc.

*Combination of Stations Reduces the Overhead Charges.* Practically all of these charges may be reduced if one power station, instead of several, supplies all the power. But one staff of executive officers need be employed, only one set of books need be kept, and one office; the cost for station attendance will not be as great as if several stations are used, etc. Also larger generators would be used in the larger station than in the smaller ones and we know that large generators have a higher efficiency than small ones.

*Necessity of Large Stations.* The use of electrical power is becoming so general that for large cities perhaps a hundred thousand killowatts of power may be required to supply all the demands. A generator to supply 100,000 kw. has never been built; the largest built so far has a capacity of 20,000 kw. Hence to supply 100,000 kw. it would require at least five of these big machines and *they would all be operated in parallel on the same bus bars.* In some large

stations as many as ten or more alternators have been installed to supply the load and they all operate in parallel.

*Number and Capacity of Machines.* The considerations which would govern the selection of the number and size of machines for any given station are the same as those discussed in Chapter III in the study of c-c. machines, operating in parallel, but they may be reviewed here. In general *it is best to have the machines in a station of the same size and type,* because only a few spare parts need be kept in stock for making repairs. Coils are likely to burn out at any time and a few should always be kept in the station for making quick repairs in case of necessity. If all machines are of the same size and type then only one set of coils need be kept on hand but if several sizes are installed in a station a proportionally greater number would have to be kept in stock. Also if the same size machines are installed there always exists the possibility of interchanging parts from different machines if necessary.

In any ordinary station there should be, however, at least one small sized machine for carrying the load during the early hours of the morning when it is very light.

*Parallel Connection of Alternators Always Used.* Having several alternators, then, in a station, to be operated on the same bus bars, the question arises as to how they shall be connected together, in series or parallel. Practically all power and lighting systems are designed for operation at *constant voltage* irrespective of the load. If the alternators were connected for series operation it is evident that the voltage on the busses would vary directly with the number of alternators operating. If for example three machines were operating in series, the bus-bar voltage would be three times as high as if one only machine were operating. *Hence it is evident that series connection of alternators would not satisfy the requirement of constant voltage.* But even if it were all right to use the series connection in so far as the load was concerned it could not easily be

done because *alternators operating in series are in unstable equilibrium*, unless the machines are mechanically coupled together. If the two alternators (not mechanically coupled) are connected in series to a load, the voltage on the load will continually vary from zero to twice that of one alternator. It is not thought worth while to further analyze this point here as it has no commercial importance.

In considering alternators operating in parallel we have three points to investigate. What precautions are necessary in connecting an alternator to bus bars already alive? What will happen if the *generated* voltage of this machine is made greater or less than that of the bus bars to which it is connected? (We emphasize the word generated because, of course, the terminal voltage of the alternator cannot be made different from that of the bus bars to which it is connected.) How may the load be divided between the different alternators, as desired by the operator? These three points will be taken up in the order named.

**65. Synchronizing.** Suppose several alternators are already operating in parallel on the same bus bars and another alternator is to be connected to these same bus bars; what conditions must be fulfilled before the switch, connecting this *incoming machine* to the bus bars, may be closed? They may be briefly stated thus:

1st. *A machine voltage equal to the voltage of the line (bus bars).*

2d. *A frequency for the machine which is the same as that of the line.*

3d. *The phase of the machine voltage opposite to that of the line.*

4th. *A machine e.m.f. wave form similar to that of the line.*

The first three conditions can be satisfied by various manipulations which the operator can carry out but the fourth cannot be accomplished by any variation of speed, field excitation, etc.

*The Wave Form Not Adjustable.* The e.m.f. wave form of an alternator is fixed by the design of the machine and cannot be affected by the operator; however, practically all modern machines give wave forms very nearly sinusoidal so that the fourth condition is nearly always satisfied to a degree sufficient for successful parallel running.

*Manipulation.* The operation of manipulating the incoming machine to bring about the first three conditions and of closing the switch which connects it to the bus bars is called **synchronizing.** It is evidently easy for the operator to satisfy the first two requirements; the voltage of the incoming machine may be varied by its field rheostat and its frequency (depending directly upon the speed) may be altered by changing the speed of its prime mover. To satisfy the third condition a *synchronizing device* may be used; *either incandescent lamps, properly connected between the machine and bus bars, or a synchronoscope* (many times called a *synchroscope*) may be used.

FIG. 158.—Oscillating Synchronoscope. Weston Elec. Inst. Co.

*The Synchronoscope.* The synchronoscope is an indicating instrument having a dial over which a finger rotates or oscillates. In the better type (illustrated in Fig. 158) the finger merely oscillates back and forth while the type shown in Fig. 159 has a circular dial and the finger rotates over the complete circle.

In either type there are two independent electrical circuits, one of which is connected to the bus bars and the other to the incoming machine. The magnetic fields set up by these two circuits so react on one another as to make the needle either oscillate or rotate; a mark on the dial shows the proper "synchronizing" position for the needle and the synchronizing switch must not be closed

until the first two conditions have been satisfied and the synchronoscope needle points to this mark.

*Use of Lamps Instead of a Synchronoscope.* Fig. 160 shows how lamps may be used on low voltage machines. If the machine were a 110-volt alternator, two 110-volt lamps


Fig. 159.—Rotating Synchronoscope. Westinghouse Elec. and Mfg. Co.

would be used; with a 220-volt alternator, 220-volt lamps would be proper, or, of course, two 110-volt lamps in series might be used instead of each 220-volt lamp.

*Difference in Frequency Shown by the Lamps or Synchronoscope.* In synchronizing, either with lamps or a synchronoscope, the incoming machine is brought up to approximately its proper speed and then its voltage is adjusted until equal to the bus voltage. In case a syn-

chronoscope is used it is then "plugged in" and it will rotate, in one direction if the incoming machine is slow and in the opposite direction if it is running too fast. The number of revolutions per second gives the *difference in frequency* between the incoming machine and the line. In case lamps are used they will flicker, being alternately bright and dark; *the number of flickers per second* gives the difference in frequency of the incoming machine and line.

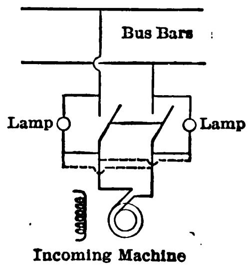



FIG. 160.—Connection of lamps for Synchronizing; "Dark" Connection in Solid Lines, "Bright" Connections in Dotted Lines.

*"Dark" and "Bright" Connections of Lamps.* If the lamps are connected straight across the switch blades (as shown by the full lines in Fig. 160), the proper time for closing the synchronizing switch is in the middle of a dark period, while if they are connected zigzag across the switch (as in the dotted lines of Fig. 160), the proper time for closing the synchronizing switch is at the center of a bright period.

*Cause of Lamps Flickering.* The reason for the flickering of the lamps may be seen by reference to Fig. 161.

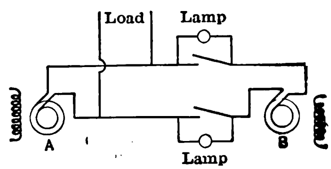



FIG. 161.—Synchronizing Lamps form Part of a Closed Circuit, Containing the Two Armatures in Series.

Machine $A$ is already supplying load and machine $B$ is to be synchronized with it. The *lamps form part of a closed*

*circuit* made up of the two armatures and the two lamps all in series. When the two e.m.fs. act together (in phase) the lamps will glow, but when the two e.m.fs. are in opposite phase (the condition required for synchronizing) there will be no resultant voltage acting in this circuit, as the two will just neutralize each other. If there is no voltage in the circuit no current will flow through the lamps and they will be dark; hence when the lamps are dark it signifies that the two e.m.fs. are in phase opposition.

*Lamps Used with High-voltage Machines.* When the machines are of high voltage, lamps cannot be used directly

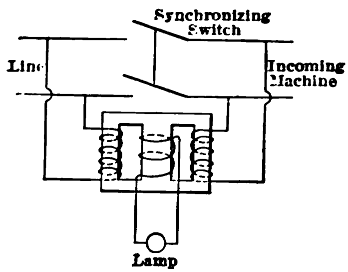



FIG. 162.—A Possible Connection for Using Low Voltage Lamp on High-voltage Circuit.

on the line, but small transformers must be used. Fig. 162 shows one scheme for using one transformer and one lamp The coils on the outside legs of the transformer core are so connected that when the two e.m.fs. are in phase opposition, no flux goes through the center leg, hence the lamp is dark and, when the two e.m.fs. are 180° out of their proper phase relation, the flux from both outside legs goes through the center leg and so the lamp glows.

*Sequence of Operations in Synchronizing.* To synchronize the incoming machine, then, the proper sequence of operations is the following: The alternator is brought up to approximately its proper speed and then its excitation

is put on and the voltage is adjusted to approximately equal that of the line; the synchronizing device is then put in the circuit and the speed is again adjusted until the difference in frequency is very small, say, ten alternations per minute (this figure will vary with different operators and different machines). A final adjustment of the voltage is now made to make it within one or two per cent of that of the line and, when the synchronizing device indicates the proper phase relation, the synchronizing switch is quickly closed. If the operator makes a bad "shot," i.e., closes the switch either too soon or too late, an excessive current will result in the armature and the protective devices will open and then another attempt must be made.

This discussion of synchronizing holds good for any synchronous machine; either alternator, synchronous motor or synchronous converter.

**66. Circulating Current.** Immediately after the alternator has been synchronized, *it takes no load at all;* in this respect it is similar to a c-c. machine which has just been paralleled with the station bus bars. When c-c. machines are operating in parallel and it is desired to have one of the machines take more load, the voltage of this generator is raised and *it will increase its load in proportion to the increase in its generated voltage.*

*Effect of Varying the Excitation of the Alternator.* If it is desired to make the incoming alternator take load the natural thing to do is to increase its generated voltage by cutting out some of the field rheostat the same as is done with a c-c. generator. *But such a procedure does not make the alternator take load at all;* the generator ammeter indicates a current almost proportional to the increase in excitation, but the generator output wattmeter gives scarcely any reading.

Fig. 163 shows the alternator connected to the bus bars through its ammeter and wattmeter. Increasing the excitation increases the reading of $A$ but does not make $W$

read to any extent. Hence this current indicated by $A$ must be a *reactive current,* 90° out of phase with the terminal voltage of the generator. The reactive current circulates between the various armatures and does not go into the load circuit at all; it is therefore called a *circulating current.*

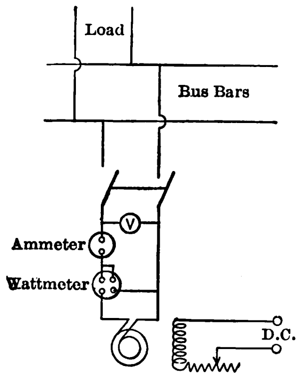



FIG. 163.—Connection of Alternator to Bus-bars, through Proper Meters.

The reason for this circulating current may be seen by reference to Figs. 164 and 165. Let us suppose only two alternators in parallel supplying some power to a load circuit; also that No. 2 has just been synchronized and so is furnishing practically none of the power to the load. Consider the local circuit made up of the two armatures and bus bars, all in series with each other. If the voltage of No. 2 is just the same as that of the bus bars (this condition is obtained before synchronizing), there is

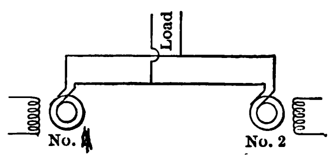



FIG. 164.—Parallel Connection of Alternators.

no resultant voltage in the local circuit and no current flows around this circuit. The vector diagram for this condition is shown in Fig. 165, where $OE_1$ gives the voltage of machine No. 1 and $OE_2$ gives that of machine No. 2. Evidently the resultant of these two e.m.fs. is zero.

*Effect of Increasing the Voltage.* If the voltage of No. 2 is increased to $OE_2'$, there is a resultant voltage $OR'$ acting in the local circuit. As the armature circuits are highly inductive, the e.m.f. will produce a current nearly 90° behind it in phase, shown in Fig. 165 by $OI'$, lagging behind $OR'$, by the angle $\theta$, where

$$\tan \theta = \frac{\text{inductance of both armatures}}{\text{resistance of both armatures}}.$$

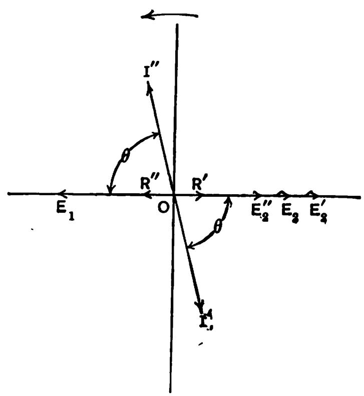



FIG. 165.—Vector Diagram of Circulating Current.

The current $OI'$ is practically 90° behind the phase of $OE_2'$, hence does not represent a load on machine No. 2; also it is practically 90° ahead of $OE_1$, and so does not represent a load on machine No. 1. It is merely a reactive current, circulating between the two armatures and representing no power in either of them.

*Effect of Decreasing the Voltage.* If the voltage of machine No. 2 is decreased to $OE_2''$, the resultant current is again reactive but opposite in phase to what it was before as shown at $OI''$ in Fig. 165; it now leads $OE_2$ and lags behind $OE_1$. This circulating current is really a magnetizing current for one machine and a demagnetizing current

for the other. When No. 2 is over-excited (i.e., excited to give a voltage higher than that generated by No. 1) the current $OI'$ tends to demagnetize No. 2 and magnetize No. 1 while current $OI''$ tends to magnetize No. 2 and demagnetize No. 1.

This circulating current of course heats the armatures and so decreases the safe current which the machines can furnish to the load circuit because the total armature current is made up of the vector sum of the load current and the circulating current.

Summing up these ideas about circulating current we may say, that if the voltage of one generator (operating in parallel with others) is altered *it does not affect the load division between the different machines but produces a circulating current which unnecessarily heats the armatures and tends at the same time to so react on the fields as to equalize the generated voltages of all machines.*

**67. Division of Load.** The next question which arises is this—if the load division between two alternators (operating in parallel on the same bus bars) is not affected by a variation of the field excitation how can the load be shifted from one machine to the other? It may be shown both experimentally and theoretically that if two machines are sharing a load equally and it is desired to have machine No. 2 take more load *this can be accomplished only by increasing the torque of the steam engine (or turbine) driving machine No. 2.*

To analyze the question let us suppose that two alternators are operating in parallel, supplying power to some outside load and that the load is equally divided between the two machines. Under such conditions the e.m.fs. of the two machines are exactly opposite in phase. We further assume that the two e.m.fs. are equal so that there will be no reactive circulating current between the two machines. The two e.m.fs. are shown by $OE_1$ and $OE_2$ ~~Fig. 166.

If the prime mover of No. 2 is given more steam it will of course try to speed up generator No. 2. *But this can occur for only a small fraction of a second, until No. 2 has pulled slightly ahead of No. 1 in phase;* the two machines must turn the same number of revolutions per minute (same number of poles on both machines assumed) because they are operating *in synchronism* with each other, so that the increased speed of No. 2 can only last during that small time while No. 2 is pulling ahead of No. 1 in phase.

After No. 2 has pulled ahead in phase its e.m.f. vector is represented in Fig. 166 by $OE_2'$, which is ahead of its original phase by the angle $\alpha$. Now the resultant of $OE_1$

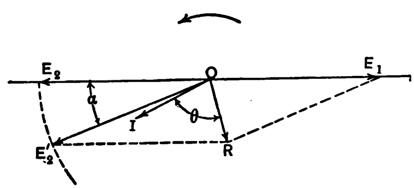



FIG. 166.—Vector Diagram to Show Load Division.

and $OE_2'$ is not zero but $OR$. This voltage acting in the local circuit will force a current through the two armatures and this current is shown in Fig. 166 by $OI$, lagging behind $OR$ by the angle $\theta$, the angle $\theta$ being the same as it was in Fig. 165.

The current $OI$ is nearly in phase with $OE_2'$ and nearly 180° *out of phase with* $OE_1$. *The result of this current is to add to the load No. 2 was already carrying, a load represented by the current OI, and to decrease the load No. 1 was carrying by the same amount.*

*The Load Varies Directly with the Phase Shift.* The value of $OR$ (hence of $OI$) depends upon the value of the angle $\alpha$ (Fig. 166) and this angle depends upon the torque of the prime mover of machine No. 2. To change the load on one of the alternators from zero to full load it is only

necessary to change $\alpha$ from zero to about 20° and for these small values of $\alpha$ it is approximately true that the load on the alternator is directly proportional to the angle $\alpha$. Experimental results, illustrating this point, are given in Fig. 167. It is shown there that for a given load increase a somewhat smaller change in $\alpha$ is required when the generator is over-excited than when it is under-excited.

The electrical operator in a large power plant generally has control of the steam supply to the various prime movers so that he can by variation of the supply, shift the load from one alternator to another as he desires.

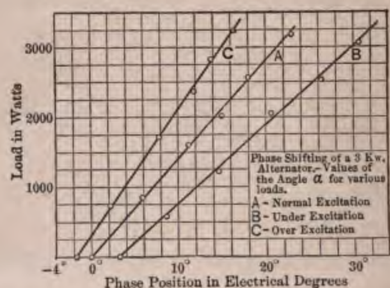



Fig. 167.—Curves Showing Phase Shift with Load Variation.

It sometimes happens that two alternators will not operate satisfactorily in parallel. The division of load is not constant; the load shifts quickly from one machine to the other and back again. The rush of current between the two machines as the load shifts from one to the other may be sufficient to open the circuit breakers and so throw the two machines out of step. Such machines are said to have a low *synchronizing power* whereas machines which operate smoothly, maintaining a fairly uniform division of load are said to have a high synchronizing power.

## CHAPTER VIII

### THE TRANSFORMER

**68. Principles Involved.** A transformer is a piece of stationary apparatus by means of which a-c. power may be changed from one voltage to another. It consists essentially of a closed magnetic circuit (made of laminated iron and called the **core**) on which are placed two coils of insulated wire, the two coils being entirely separate and insulated from one another. (This later qualification will be modified when discussing a special type called the *autotransformer.*) The two coils generally have a widely different number of turns; a certain transformer, for instance, has 93 turns in one coil and 1800 in the other.

*Exciting Current.* One of the coils (called the **primary**) is connected to an a-c. line of suitable voltage and the resulting current which flows (the other coil being open circuited) serves to magnetize the iron core; it is called the *exciting current.* The magnetic flux through the core will evidently be an alternating one, being in one direction with positive current and in the reverse direction when the current has reversed; hence any turn of wire surrounding the core will have induced in it an e.m.f. because of this varying flux.

*Induced E.M.F. in the Secondary Coil.* The second coil (the one to which power is *not* supplied, called the **secondary**) is also wound on the core and therefore will have an e.m.f. induced it. Lamps, motors, etc., may be connected to this secondary coil and will be supplied with power just as well as though they were connected to the line which

is feeding power to the primary coil. The terms "high-tension coil" and "low-tension coil" are often used instead of the terms "primary coil" and "secondary coil."

*The power input to the primary depends directly upon the amount of power being supplied by the secondary.* It is not at once evident how the power gets from the primary to the secondary and we will first consider that point.

*Equation of the Transformer.* Fig. 168 represents an elementary transformer, having a laminated, closed magnetic circuit, core $A$, a primary coil, $B$, and a secondary coil, $C$.

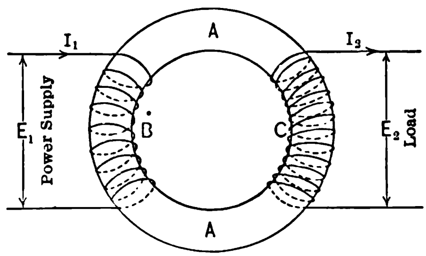



FIG. 168.—View of Elementary Transformer.

Let $I_1$ = the primary current;
$I_2$ = the secondary current;
$N_1$ = the number of turns in the primary coil;
$N_2$ = the number of turns in the secondary coil;
$R_1$ = the resistance of the primary coil;
$R_2$ = the resistance of the secondary coil;
$e_1$ and $E_1$ = the primary impressed voltage (instantaneous and effective);
$\phi$ = the magnetic flux in the core at any time.

The impressed e.m.f. of the primary must be balanced by the reacting forces in the primary coil, so we may write (for an open-circuited secondary)

$$e_1 = R_1 i_1 + N_1 \times (\text{the rate of change of flux}) \quad . \quad (64)$$

where

$R_1i_1$ = the resistance reaction;

$N_1\times$(the rate of change of flux) = the back e.m.f. of self-induction.

In ordinary transformers the term $R_1i_1$ is very small compared with $N_1\times$(the rate of change of flux), so that we may neglect it without introducing an appreciable error. We may therefore write

$$e_1 = N_1 \times (\text{rate of change of flux}), \quad . \quad . \quad (65)$$

or, in virtual values,

$$E = 2\pi f N_1 \phi_{eff}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (66)$$

*Effective Flux in the Core Constant.* From this equation we see that there must always be a certain flux (effective) through the core in order to balance the e.m.f. impressed on the primary; this flux must exist in spite of any demagnetizing action the secondary current may produce.

*Increase in Primary Current to Balance the Demagnetizing Effect of a Secondary Current.* For a secondary current equal to zero there exists a small magnetizing current in the primary; if some load is put on the secondary so that its current is some value $I_2$ the secondary coil will produce a demagnetizing action on the core equal to $.4\pi N_2 I_2$. But the primary current must always be sufficient to produce in the core the flux $\phi_{eff}$, hence when the secondary current increases, the primary coil automatically draws from the line an increased current. *This increase in primary current will be just sufficient to overcome the demagnetizing action the secondary current has produced.*

*Ratio of Currents.* We may, therefore, put

$$.4\pi N_1 I_1' = .4\pi N_2 I_2, \quad . \quad . \quad . \quad . \quad . \quad (67)$$

where $I_1'$ is the increase in $I_1$ to overcome the demagnetizing effect of $I_2$. But as the magnetizing current of a trans-

former is very small compared to its full load current (generally about 5%), we may put, without much error,

$$.4\pi N_1 I_1 = .4\pi N_2 I_2, \quad . \quad . \quad . \quad . \quad . \quad (68)$$

or

$$N_1 I_1 = N_2 I_2, \quad . \quad . \quad . \quad . \quad . \quad . \quad (69)$$

which gives the approximate fundamental relation between the currents in the primary and secondary. This may be stated in words thus: *The primary ampere-turns are always just equal to the secondary ampere-turns* (*the magnetizing current being neglected*).

*Ratio of Voltages.* If all the flux which the primary produces threads the secondary coil (and this is approximately true), the volts generated per turn will be the same in each winding. If we call this voltage $e$, we must have

$$E_2 = N_2 e. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (70)$$

and

$$E_1 = N_1 e. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (71)$$

Equation (71) is true because the right-hand member is the counter e.m.f. of self-induction and this must be equal to the impressed e.m.f. (approximately).

Substituting (70) and (71) in (69), we have

$$E_1 I_1 = E_2 I_2. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (72)$$

This is the approximate equation for apparent power in the two coils. Also from (70) and (71) we get the relation

$$E_1/E_2 = N_1/N_2, \quad . \quad . \quad . \quad . \quad . \quad . \quad (73)$$

which is the fundamental voltage relation in the two coils. Expressed in words this relation is: The primary voltage bears the same relation to the secondary voltage as the number of turns in the primary coil bears to the number of turns in the secondary coil. Of course, from equation (72)

it is seen that any change in voltage must be accompanied by a change in current in the opposite sense.

Equations (69), (72), and (73) give only the approximate relations of the transformer quantities; the derivation of the exact relations requires us to consider the loss due to hysteresis and eddy currents in the core, the $I^2R$ losses in the windings, and the magnetic leakage.

**69. Commercial Importance of the Transformer.** From the previous simple analysis it is seen that, by means of a transformer a-c. power may be changed from one voltage to another; if the secondary coil has more turns than the primary, the voltage will be raised (i.e., "stepped up") and if the secondary coil has fewer turns the voltage will be lowered ("stepped down"). Some of the greatest power developments to-day are hydro-electric (using water turbines for prime movers) in which the power station must be situated close to the falls, the power of which is being used. The place where the electric power is consumed may be a hundred miles or more distant, so that a *long distance transmission line* is necessary to carry the power to the place of consumption.

*Long Distance Transmission Requires a High Voltage.* It is commercially impossible to carry electric power any great distance unless high voltage is used, because of the high $I^2R$ losses in the line, or else the heavy investment for the copper wires. An approximate rule for the voltage of ordinary transmission lines is from 500 to 1000 volts per mile length of the line. A line 150 miles long might be run at 80,000 volts or 100,000 volts, although special conditions may cause departure from this rule.

*Location of Transformer in a Power-transmission System.* These high voltages cannot be generated directly in an alternator, neither can the power be supplied to the consumer at such a high voltage, hence the problem the electrical engineer has to face is this: The power may be generated at medium voltages (2300–11,000 volts), must

be transmitted at high voltage (perhaps 50,000–120,000 volts), and must be supplied to the customer at low voltage (110–440 volts). The transformer raises or lowers the voltages where required and, without the transformer, the successful development of a-c. transmission systems would have been impossible.

Fig. 169 shows how the transformer forms links in a transmission and distribution system. For railway substations the voltage is changed, in one step, from the line

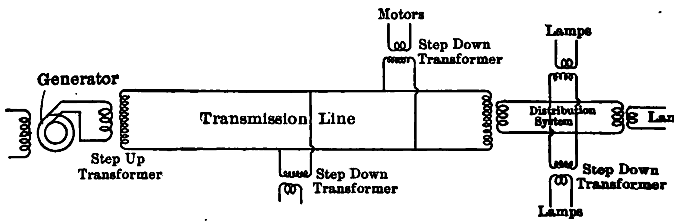



FIG. 169.—Diagram of Power Transmission System, Showing Service Performed by Transformers.

voltage to that required in the substation; for lighting work the high voltage of the transmission line is generally stepped down by a few large transformers to 2300 volts, and is then distributed throughout the city at 2300 volts to small transformers located on the poles which step it down again to 110 volts.

Each of these small transformers (generally of less than 15 kv-a. capacity) supply perhaps 25 to 50 customers. Fig. 170 shows one of these small transformers located on a pole, just under the cross arms; in the cut only the outside containing case of sheet iron can be seen because the coils and core are always put inside cases to protect them from moisture, dirt, mechanical injury, etc. The small wires going into the case at the back (next the cross arms) are the 2300-volt wires and the larger wires coming from the front are the 220-volt wires which connect directly to the lighting wires in the customer's house.

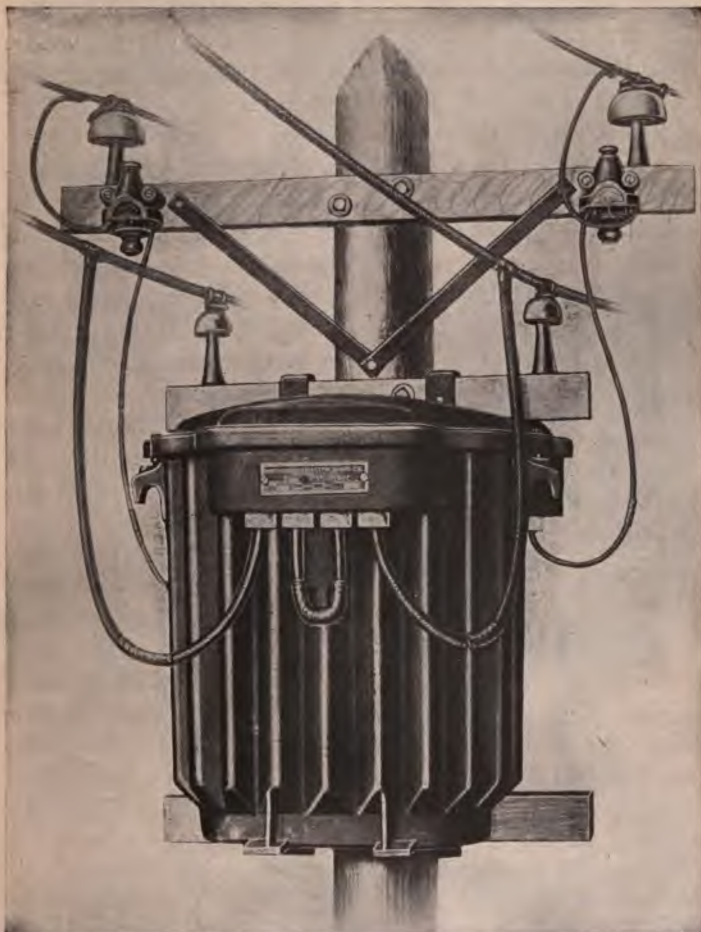


FIG. 170.—Small Transformer Located on a Pole; the Two High-tension Wires Enter at the Back and the Low-tension Wires Come Out at the Front (i.e., the side not adjacent to the pole). Westinghouse Elec. and Mfg. Co.

**70. Construction.** In actual construction the transformer does not resemble at all that given in Fig. 168. The cores can be most economically built up of rectangular, instead of circular, sheets, and the two coils are always placed as closely together as possible.

*Two General Types.* Two types of transformers have been developed in which both of these ideas are incorporated; they are the **core type** and the **shell type.** In both these types the cores are built up of thin sheets of iron, generally rectangular in shape, and the primary and secondary coils are placed in very intimate relation with one another.

FIG. 171.—Small Core-type Transformer, Completely Assembled. General Electric Co.

*Core Type.* The core type closely resembles the elementary transformer shown in Fig. 168; however the shape of the core is rectangular (its cross-section is nearly square) and the two coils are placed one over the other as close together as possible. Each coil is divided into two sections, the two sections being placed on opposite legs of the core. Fig. 171 shows a view of an assembled core-type transformer ready to be placed in its containing case. Space is left between the two coils so that oil for cooling purposes may circulate through the windings.

*Shell Type.* The shell-type transformer is shown in Fig. 172. The coils of the core type are generally cylindrical in form but in the shell type they form a rectangular structure (as shown in Fig. 173) *similar in form to the core of the core type,* and the laminations (sheets of which the

core is made) are built up around two legs of the assembled coils.

*Lamination of Coils.* In order that the primary and secondary coils may be placed closely together, they are built up in thin sections (called "pancake" coils) and the sections of the two coils are sandwiched together, first a thin section of the primary, then one of the secondary, etc.

FIG. 172.—A Small Shell-type Transformer, Completely Assembled. Fort Wayne Electric Works.

One of these thin sections is shown in Fig. 174. In Fig. 177 is shown a cross-section of the assembled coils showing how the sections are interspersed; there may be a dozen or more of these sections in a large transformer. Fig 175 shows another method of winding shell type transformers; here pan-cake coils were not used but the two coils are placed intimately together by having the low tension coil

built in two parts, the high tension coil being placed between the two sections of the low tension coil.

*Construction of the Core.* Although the iron core of a modern transformer forms a continuous iron path around the coil, the laminations in the form of a hollow rectangle, are not in one piece, because if such were the case, the coil would have to be wound through them instead of being built up independent of the core.

FIG. 173.—Coils for a Shell-type Transformer, Showing How One Coil is Placed Over the Other. Westinghouse Electric and Mfg. Co.

Each lamination is made of two pieces as shown by the full lines of Fig. 177. In stacking them up around the coils, every other one is reversed so that the joints come as shown by the dotted lines. Because of this alternation of the joints, the core, when built up and clamped together, is very solid and has but little more reluctance than it would have if each lamination were one solid piece.

The most recent type of construction is really a modification of the core type; a view of one of these transformers removed from containing case is given in Fig.

178, from which it may be seen to resemble a core-type transformer having winding on but one leg. The other

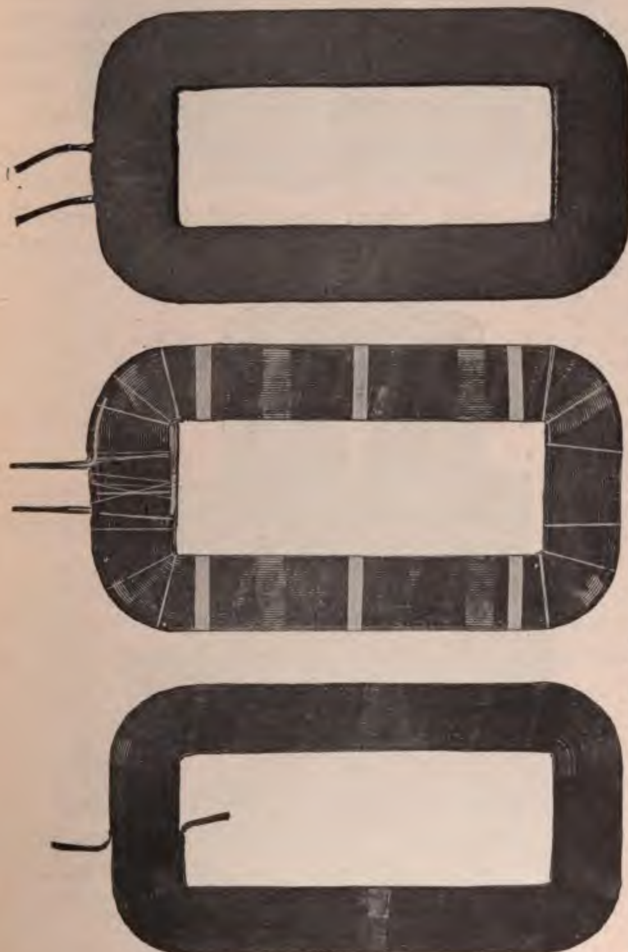


FIG. 174.—A Pan-cake Coil, Before and After Insulating. Westinghouse Electric and Mfg. Co.

leg, used as a return path for the magnetic flux, is divided into four parts, symmetrically disposed around the center

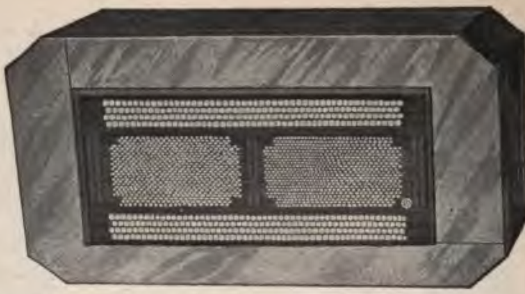


FIG. 175.—Cross-section through Transformer Coils, Showing how They may be Interspersed. The fine wire is the high-voltage winding.

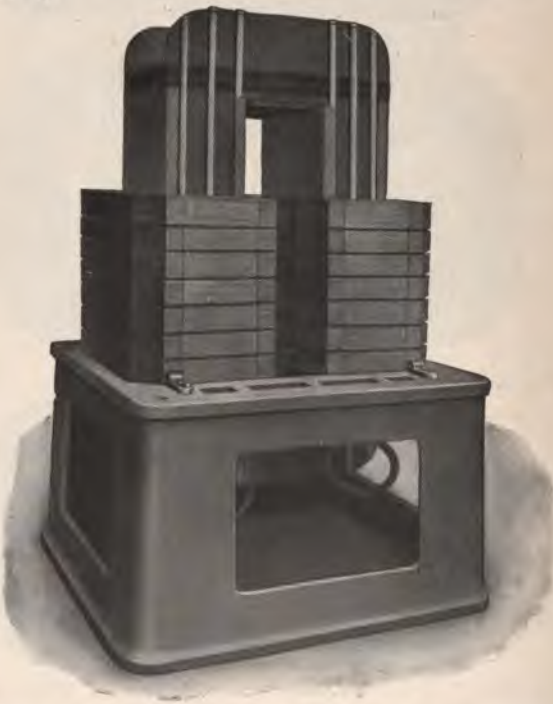


FIG. 176.—This Cut Shows how the Coils of a Transformer are First Assembled and Then the Core Built up around Them.

leg, on which the coils are placed. This type uses concentric, cylindrical coils (which are the easiest to manufacture), is compact in its arrangement, and is more easily cooled than either of the other types. A sketch of the transformer is given in Fig. 179; it shows how freely the cooling oil may circulate between the coils and around all parts.

*Size of Wire in Transformer Coils.* The size of wire used on the two coils is not the same; it is much smaller for the high-voltage coil than for the low-voltage coil. The

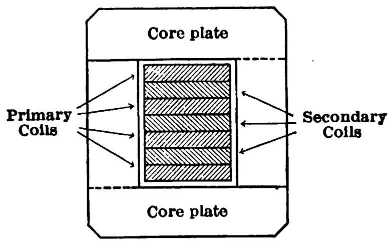



FIG. 177.—The Laminations, in the Form of Hollow Rectangles, are Split so That They May be Put around the Sides of the Coils.

most efficient design is one in which the $I^2R$ in the primary coil is equal to that in the secondary. We have shown in equation (72) that $I_2/I_1 = E_1/E_2$, or, in other words, the currents in the two coils are in the inverse ratio of their voltages. Let us put

$$E_1/E_2 = a, \text{ the ratio of the transformer.}$$

Then $I_2 = a\, I_1$ and if we are to have

$$I_2^2 R_2 = I_1^2 R_1, \text{ then evidently}$$

$$a^2 R_2 = R_1. \quad \quad (74)$$

If for example a transformer has a ratio of 20:1, the high-voltage coil should have 400 ($=20^2$) times as much resist-

ance as the low-voltage coil. Now there are twenty times as many turns on the high-voltage as on the low-voltage

FIG. 178.—View of General Electric Type *H* Transformer.

coil so that *the cross-section of the high-voltage coil should be* $\frac{1}{a}$ *times that of the low-voltage coil.* This ratio of cross-sections

gives approximately *the same weight of copper for both coils.*

Transformers designed with this ratio, however, will get hotter in the high-voltage coil than in the low-voltage coil because, owing to the greater thickness of insulation around the high-voltage coil, it is more difficult for the heat to escape from the copper. In practice, therefore, a somewhat greater weight of copper is used in the high-voltage winding than in the low-voltage.

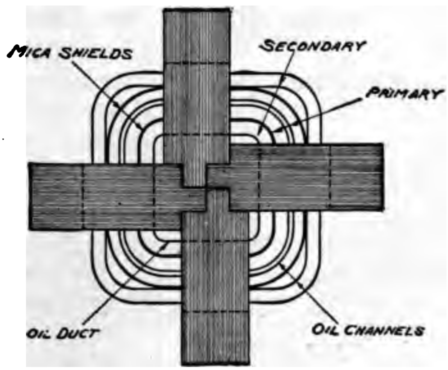



FIG. 179.—Plan of General Electric Type *H* Transformer, Showing how the Oil May Circulate around and between the Coils.

*Insulation of Windings.* The insulation of the windings of a transformer must be very carefully looked after because of the high voltages to which a transformer is subjected. The high-voltage coil must be insulated not only from the low-voltage coil, but also from the core; a breakdown in the insulation in either of these places would connect to the high-voltage line a part of the transformer on which the operator supposes there is either a low voltage or none at all and he would probably receive a fatal shock in working around the transformer. Or a customer touching what he supposes to be a low-voltage line might receive

the period of acceleration the field of the synchronous motor is left without excitation; after synchronous speed has been reached it is gradually excited and, if the *armature current decreases, the excitation is increased until the normal value is obtained.* It sometimes happens that the armature pulls into synchronism with improper polarity, in which case the *armature current will increase as the field current is increased.* Some method must then be used to pull the armature "into step" (correct polarity), such as re-starting.

*High Starting Current and Low Torque.* The current taken from the line for starting a synchronous motor in this manner is generally two or three times the full-load current, but in spite of this large current the starting torque is not high unless the machine has been properly designed. It was said that this method of starting depended upon the reaction of the eddy currents in the pole faces, but with a laminated pole we know these currents cannot be high because of the subdivision of the path for the eddy currents. To give a fair starting torque in this case it is necessary to put in the pole faces **damping grids** or **amortisseurs.**

*Damping Grids in Pole Faces.* These consist of heavy bars of copper imbedded in slots in the pole face (the direction of the slots is parallel to the armature shaft) and short circuited at their ends by a copper band surrounding the pole. In fact, these grids, cross-bars and band, are sometimes made in one piece, a copper casting. These grids form low-resistance paths for the eddy currents and so help to produce a good starting torque. They also tend to damp out oscillations of the armature (called "hunting")* and from this action they derive their name. In Fig. 201 are shown some poles of a synchronous motor on which the damping grids may be seen.

* See page 327 for explanation of this term.

and at least twice * the voltage for which the high-voltage coil was designed.

*Higher Insulation on First Turns.* In order to protect transformers from the high voltages due to *surges* (electrical oscillations in a transmission line) it is customary to insulate the first few turns of the high-voltage winding much better than the rest of the turns. It is found in practice that a transformer not so built, nearly always breaks down in these first turns.

**71. Methods of Cooling.** Due to the losses which occur in the core and windings of a transformer it heats up the same as any other piece of electrical apparatus. But the heating in a transformer would be very exaggerated unless means were taken to prevent it as there are no moving parts to create air currents and so dissipate the heat. Special means are always used to keep down the temperature of a transformer.

Air cooling, oil cooling, or water cooling may be employed; that most generally used for small transformers being the oil cooling and for large transformers in power plants, water cooling.

*Air-cooled Transformers.* In the air-cooling method a fan is used to force cool air from the bottom of the transformer, past the windings and core to carry off the heat from the top of the transformer. Sometimes the fan connects to a *pressure chamber* in the basement of the station and the row of transformers is placed directly over this chamber. The bottom of each transformer case is open and connects to the chamber below; the air pressure used in the chamber depends upon the load the transformers are carrying, being sufficient at heavy loads to send a very swift air current through the transformers. The air should be well cleaned otherwise dirt and foreign particles will

* This figure varies for different transformers being greater for low-voltage than for high-voltage transformers.

collect in the transformer case and tend to cause short circuits, etc. Air cooling is not used to a great extent.

*Oil-cooled Transformers.* The method of cooling most generally used is to place the transformer in a water-tight case, *filled with oil.* The oil serves both as an insulator and as a cooling medium. Currents circulate in the oil due to convection. These currents are "up" next to the transformer core and coils and "down" on the outside, next to the case. The heat is carried by the oil currents from the transformer to the case, through which it is conducted to the atmosphere. The direction of these currents is shown in Fig. 181.

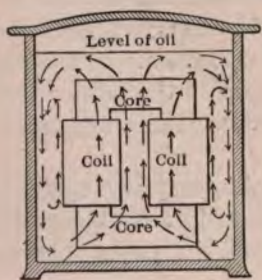


FIG. 181.—Arrows Show Direction of Oil Currents Around a Transformer.

The use of oil in a transformer increases its capacity in the same way that forced ventilation increases the capacity of a motor or generator. This method of cooling is the most reliable there is; there is nothing to get out of order as in the case with air or water cooling.

In the larger sizes difficulty is encountered because of the great amount of heat generated in the transformer; the smooth-iron case does not expose enough surface to the air for proper cooling. Because of this the case is made of *corrugated metal,* as shown in Fig. 182, so that the radiating surface of the case is very much increased. But in very large station transformers the heat cannot be radiated fast enough even with a corrugated case, so that resort is had to water cooling.

*Water-cooled Transformer.* A water-cooled transformer is one in which the transformer is immersed in oil (as in the oil-cooled transformer) but the oil itself is cooled by *circulating* between coils of pipes, immersed in the oil, through

which pipes cold water is circulating. This method of cooling is required in very large transformers such as are frequently located in stations. Evidently the method could not be

FIG. 182.—Transformer Case Built of Corrugated Steel, to Give Greater Cooling Surface. General Electric Co.

used for transformers located on poles or in out-of-doors installations because of trouble due to the freezing of the water, etc. A large water-cooled transformer removed

is called the "pull-out" point; generally this is between 75 and 150% overload.

*Use of Synchronous Motors.* Speed-load curves for two motors are given in Fig. 204. The shape of these curves shows that the synchronous motor is entirely unsuited for loads requiring a variable speed, such as railway work, or for driving machine tools. Its principal use is in frequency-changing motor-generator sets.

Such motor-generator sets are generally used in connection with 25-cycle transmission lines. A 25-cycle synchronous motor is direct connected to a 60-cycle generator

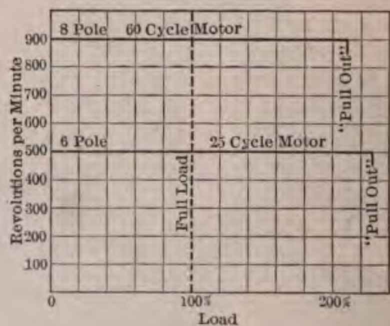



FIG. 204.—Speed-load Curves for Synchronous Motors.

which furnishes power to local lighting circuits. This transformation is necessary because 25 cycles per second is too low to use for lamps as bad flickering results. The synchronous motors of these sets are also used to regulate the power factor of the transmission line, as described in a later paragraph.

**82. Phase Characteristics or "V" Curves.** Suppose a synchronous motor is running light and that the field current is at its normal value; the armature current will be quite small, in fact, just enough to supply the no-load losses. *If, now, the field current is altered, either above or*

load, each of them being from 1 to 3% of the full-load capacity of the transformer. The larger percentage applies to the smaller sizes.

*Core Loss.* The core loss in a transformer is due to hysteresis, and also to the eddy currents, which are set up in the laminations of which the core is built.

As explained in Chapter I, it requires energy (work) to carry iron through cycles of magnetization, a measure of this energy being the *area of the hysteresis loop*. As it is desired to keep this loss in the transformer as low as possible, the iron for transformer cores is carefully selected; only that grade of iron which has a narrow hysteresis loop is used. For a given transformer the hysteresis loss *varies directly with the frequency and with the 1.6 power of the maximum flux density.*

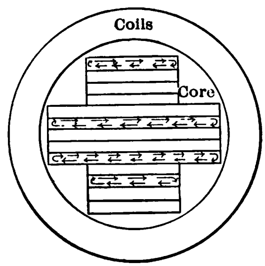


FIG. 184.—Sketch Showing the Nature of the Paths Taken by Eddy Currents in a Transformer Core. Here the laminations are shown much thicker than they really are used in transformers.

The eddy currents in the core circulate in the laminations as shown in Fig. 184, in which the laminations are represented as much thicker than they really are. These currents heat the iron and so represent loss in the transformer. This loss is kept low by using thin laminations as explained in Chapter II. Fig. 184 gives the cross-section of one leg of a core type transformer.

For a given transformer the eddy current loss *varies with the square of the frequency and with the square of the maximum flux density.*

*Core Loss Independent of Load.* The flux density in a transformer is nearly *independent of the load on the secondary* and, as the frequency of the supply current does not vary with the load, we may conclude that both hysteresis and

eddy current losses are independent of the load; hence the core loss (which is the sum of these two) *is independent of load.*

*Copper Loss.* The $I^2R$ loss in the windings evidently increases with the square of the load current. This is true for both transformer coils because we have previously shown that the primary current increases proportionately with any increase in the secondary current. The total copper loss may be calculated from the equation:

$$\text{Copper Loss} = I_1^2R_1 + I_2^2R_2 = I_1^2(R_1 + a^2R_2), \quad . \quad (75)$$

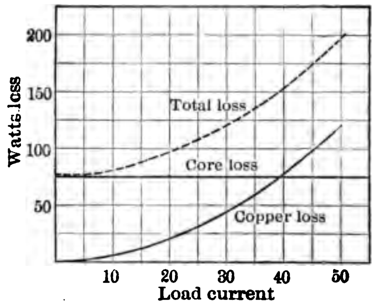



FIG. 185.—Curves of Losses in a Transformer, Showing Their Variation with Load.

where the term $(R_1 + a^2R_2)$ is called the *effective resistance of the transformer* (of both coils) *in terms of the primary resistance.*

*Loss Curves.* Fig. 185 shows the two loss curves of a 4-kv-a. transformer plotted against the secondary current; the total loss curve is obtained by adding the two.

From the total loss curve the efficiency can easily be calculated. We know that

$$\text{efficiency} = \text{output}/\text{input} = \text{output}/\text{output} + \text{losses}.$$

Now assume any output, as for example, 10 amperes. As this transformer is rated 2200 volts–110 volts, the

output$=110\times10=1100$ watts. By reference to the "total loss" curve we see that the losses in the transformer for 10 amperes output amount to 80 watts.

$$\text{Hence the efficiency of this output} = \frac{1100}{1100+80}=93.3\%$$

$$\text{At 20 amperes output the efficiency} = \frac{2200}{2200+92}=96.0\%$$

$$\text{At 30 " " "} = \frac{3300}{3300+120}=96.5\%$$

$$\text{At 40 " " "} = \frac{4400}{4400+153}=96.7\%$$

$$\text{At 50 " " "} = \frac{5500}{5500+195}=96.6\%$$

*Form of Efficiency Curve.* The efficiency curve is, thus predetermined and has the shape given in Fig. 186. This method of calculating efficiency is not rigidly correct because the secondary voltage does not remain quite constant as we have assumed. The resulting error is, however, practically negligible.

*Power Factor Curve.* The power factor curve of the primary circuit (supposing a non-inductive secondary load) has the shape given in Fig. 186. The power factor is about .30–.40 at no load and quickly rises to approximately 1.00, maintaining this high value until the transformer is heavily overloaded.

*Decrease in Secondary Terminal Volts as the Load Increases.* The secondary voltage falls slightly with an increase of load (a constant impressed primary voltage being assumed), the total change from no load to full load being 2–5%, expressed as a percentage of the full-load voltage. This percentage is called **the regulation** of the transformer. Its value depends upon the *resistance* of the windings and the

*magnetic leakage;* an increase in either of these factors producing an increase in the regulation.

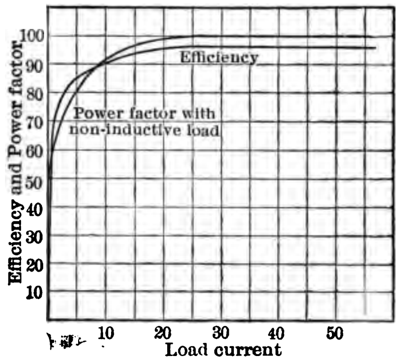



FIG. 186.—Power Factor and Efficiency Curves of a Small Transformer.

*Magnetic Leakage.* The magnetic field, upon which the operation of the transformer depends, is generated by the primary coil; all of this magnetic flux does not thread the secondary winding as some magnetic lines leak

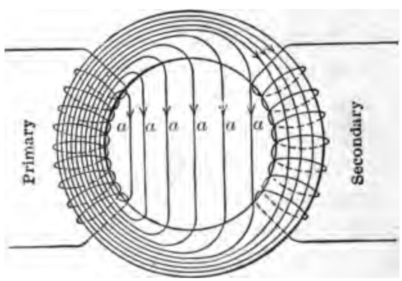



FIG. 187.—An Elementary Transformer, Showing Leakage Flux at $a$, $a$, $a$, etc.

across from one part of the core to another without interlinking with the secondary coils. In the elementary form of transformer, shown again in Fig. 187, the leakage flux takes the path indicated at $a$,$a$, etc, while the normal flux

threads both the secondary and primary. The amount of leakage depends directly upon the load, because the secondary current produces a back m.m.f. on the magnetic circuit, forcing out of the secondary more and more flux as the load increases. It is disadvantageous to have much leakage in a transformer because of the poor regulation which results; the two coils, primary and secondary, are, therefore, placed as close together as possible.

**73. All-day Efficiency.** The "all-day" efficiency of a transformer is a very important factor for the central station manager to consider; in fact it is much more important than the efficiency as ordinarily defined.

*Meaning of "All-day Efficiency."* By all-day efficiency is meant the ratio of watt-hours output to watt-hours input during a whole day's operation. An example will make this clear. Suppose a 5-kv-a. transformer is supplying a lighting load; it would, in a normal day's run, operate at full load $1\frac{1}{2}$ hours and perhaps at half load $1\frac{1}{2}$ hours; during the rest of the day there would be no load on the transformer. Suppose the iron loss is 200 watts and the full-load copper loss ($I^2R$) is 200 watts; the copper loss at half load would be equal to $(\frac{1}{2})^2 \times 200$ watts $= 50$ watts.

The transformer is connected to its supply line all day so that the core loss for all day $= 24 \times 200 = 4800$ watt-hours.

The copper loss for the $1\frac{1}{2}$ hours full load $= 1\frac{1}{2} \times 200 = 300$ watt-hours and during the $1\frac{1}{2}$ hours half load $= 1\frac{1}{2} \times 50 = 75$ watts, so that the total copper loss for the day's run is 375 watt-hours. The total loss in the transformer for 24 hours $= 4800 + 375 = 5175$ watt-hours.

The energy output in one day $= 1\frac{1}{2} \times 5000 + 1\frac{1}{2} \times 2500 =$ 11,250 watt-hours.

The energy input in one day $= 11{,}250 + 5175 = 16{,}425$ watt-hours.

$$\text{The all-day efficiency} = \frac{11250}{16425} = 68.5\%.$$

Now the efficiency of this transformer in the ordinary sense

$$=\frac{5000}{5400}=92.7\%.$$

*Proper Design to Get High All-day Efficiency.* If the transformer were redesigned (so as to have the same full-load efficiency) with 100 watts iron loss and 300 watts copper loss at full load the all-day efficiency would be better than before.

Core loss, 24 hours $=24\times100=2400$ watt-hours.

Copper loss, 24 hours $=1\frac{1}{2}\times300+1\frac{1}{2}\times75=562$ watt-hrs.

Output in 24 hours $=11{,}250$ watt-hours (the same as before).

The all-day efficiency $=\dfrac{11250}{11250+2400+562}=79.3\%.$

It is therefore evident that if a transformer is to be used for a service on which the full load demand exists for a short time only, the transformer should be designed with as low a core loss as possible, even if the $I^2R$ loss is much increased thereby. This idea must not be carried too far, however, because a transformer with high resistance regulates poorly and it would be unsatisfactory for supplying the power for lamps.

**74. Determination of Losses.** The iron loss in a transformer is easily determined by reading the watts input (at normal voltage and frequency), when the secondary is open circuited; connections as in Fig. 188. Although this wattmeter reading does include a small $I^2R$ loss due to the exciting current, it is ordinarily not considered because it is so small. The total wattmeter reading is reckoned as core loss.

To determine the full-load copper loss connections are made as in Fig. 189, *a very low voltage* being impressed on the primary. This voltage is increased until the ammeter in the short-circuited secondary indicates the full-load cur-

rent. A reading of the primary wattmeter then gives the *full-load copper loss in both coils.* (There is a very small core loss included in this reading but it is ordinarily neglected.) The copper loss for other loads may be determined by proportionality, if desired, without actually measuring them. For instance, the half-load copper loss will be one-quarter of the full-load loss; the quarter-load loss will be one-sixteenth the full-load loss, etc.

The reading from these two tests may also be used to predetermine the power factor and the regulation of the transformer; the student is referred to more advanced text-books for the method.

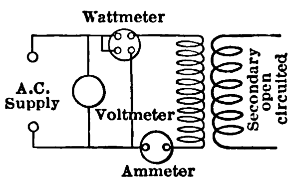



FIG. 188.—Connection of Meters for Iron Loss Determination.

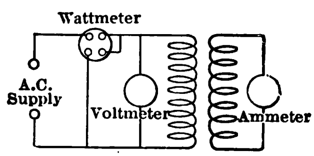



FIG. 189.—Connection of Meters for Copper Loss Determination.

**75. The Autotransformer.** This name is applied to an ordinary transformer, the coils of which are connected together electrically. Generally, the two coils of a transformer *are connected together only by the magnetic field,* but in the autotransformer *they are connected together not only magnetically but also electrically.*

*Example of an Autotransformer.* Suppose an ordinary 1100-volt/110-volt transformer, the coils of which are electrically connected together, as shown in Fig. 190. Now, instead of taking the secondary line from *c–d,* as would ordinarily be done, let the secondary load be taken from the points *d–e.* The voltage of this secondary circuit will be that of the primary, increased or decreased by the voltage generated in the coil *c–d.* If the coil *c–d* acts in the circuit

is called the "pull-out" point; generally this is between 75 and 150% overload.

*Use of Synchronous Motors.* Speed-load curves for two motors are given in Fig. 204. The shape of these curves shows that the synchronous motor is entirely unsuited for loads requiring a variable speed, such as railway work, or for driving machine tools. Its principal use is in frequency-changing motor-generator sets.

Such motor-generator sets are generally used in connection with 25-cycle transmission lines. A 25-cycle synchronous motor is direct connected to a 60-cycle generator

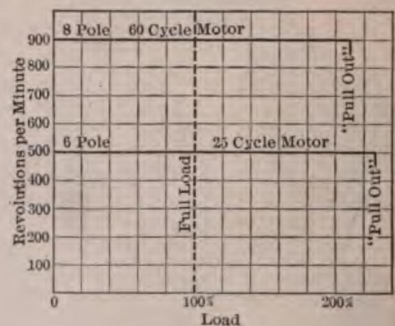



FIG. 204.—Speed-load Curves for Synchronous Motors.

which furnishes power to local lighting circuits. This transformation is necessary because 25 cycles per second is too low to use for lamps as bad flickering results. The synchronous motors of these sets are also used to regulate the power factor of the transmission line, as described in a later paragraph.

**82. Phase Characteristics or "V" Curves.** Suppose a synchronous motor is running light and that the field current is at its normal value; the armature current will be quite small, in fact, just enough to supply the no-load losses. *If, now, the field current is altered, either above or*

Because of this neutralization of currents, the auto-transformer is very economical in the use of copper, *especially when the secondary and primary voltages are nearly the same.*

**76. The Constant-current Transformer.** For arc lighting, the high voltage series system has proved to be commercially successful and most arc light systems are of this type. The arc lamps used in such work are of the *constant current type* and requires a transformer which supplies a constant secondary current.

*Constant Current System Requires Variable Voltage.* In the operation of a series arc system it often happens that some lamps go out, for some reason or other, and of course this changes the resistance of the load circuit. If the voltage impressed on the circuit were constant, the current would rise and fall as the number of lamps burning is decreased or increased and the lamps would operate poorly. Hence there is required in the station a transformer the *secondary voltage of which varies with the number of lamps in circuit.*

FIG. 193.—View of a Constant-current Transformer. General Electric Co.

*Operation of the Constant-current Transformer.* The constant-current transformer accomplishes this variation by a variation of the leakage flux between the primary and secondary. The secondary coil is made movable and the primary fixed and the leakage flux will evidently depend upon the separation of the two. A view of this type of transformer is given in Fig. 193. (This type is sometimes called the "tub" transformer.) The secondary coil is suspended and nearly counterbalanced so that but little force is required to move it up, or to separate it from the primary.

The operation may be understood by reference to Fig. 194, which shows a simplified cross-section of a constant current transformer. The leakage flux is shown in dotted lines, and the leakage path is made noticeably large in such a transformer.

*Principle on which Operation Depends.* The weight used for counterbalancing the secondary is not quite sufficient to make the coil float, but, of course, when the secondary is carrying current, the leakage lines repell the coil and help the counter weight to make the coil float. This force of repulsion is proportional to the current and *the coil is under-counter-balanced to such an extent that when the rated secondary current is flowing the coil floats.* If more than rated secondary current flows, the secondary is repelled farther from the primary, so that more leakage flux is produced. But the more leakage there is the lower is the secondary voltage and so the secondary current lowers and reduces to its proper value.

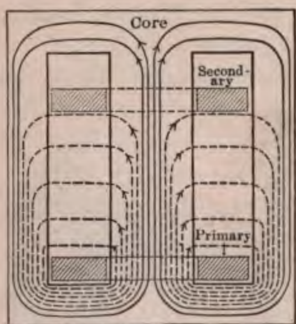


FIG. 194.—Flux Distribution in a Constant-current Transformer.

*Illustration of the Action.* Suppose the transformer is operating on a certain load of series arc lamps and one lamp goes out, thus reducing the resistance of the external circuit. The secondary current will immediately increase, thus increasing the repelling force between the secondary and primary and raising the secondary coil. But this decreases the generated e.m.f. in the secondary coil because of the increase in leakage flux and so the secondary current decreases to its normal value. Hence we see that this type of transformer will give a constant secondary current so

long as the secondary coil is floating free on the leakage flux.

*Characteristics of this Type of Transformer.* Because of the excessive leakage flux the primary of such a transformer has a rather low power factor; the value of the power factor depends upon the separation of the coils, being smaller, the greater the separation. The efficiency of this type of transformer is somewhat lower than that of a constant potential transformer. This is due to the construction; there is more iron in the core and more resistance

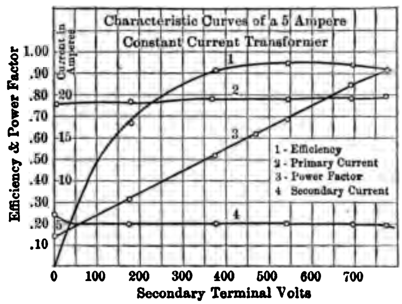



FIG. 195.—Characteristic Curves of a Constant-current Transformer.

in the coils than there would be for a constant potential transformer of the same capacity.

The characteristic curves of a constant current transformer are given in Fig. 195, in which are reproduced the results of a laboratory test on a small constant current transformer. Because of the low power factor and the efficiency at light loads, it is customary to have several taps on the secondary and to use that tap which makes the transformer operate (on a given circuit) with its secondary close to the primary, thereby producing a high power factor. To prevent violent oscillation of the secondary coil as the load varies, a dash-pot is employed which prevents rapid motion of the secondary. From Fig. 195 it may be

seen that the *primary current as well as the secondary current* of such a transformer is practically independent of the load. The explanation of this would require more space than can be afforded here.

**77. Special Types of Transformers.** For various purposes special transformers are used and we shall describe briefly here the **welding transformer, the instrument transformer,** and the **testing transformer.**

*Welding Transformer.* The welding transformer is designed for the purpose of making welded joints by heating the junction of the metal with an electric current. The two pieces to be joined are clamped tightly together and the secondary of the transformer is short circuited through this contact. Of course the resistance of the contact is high as compared to that of the rest of the secondary circuit and it becomes intensely heated. After a few seconds the two pieces fuse together at the joint. When they fuse the contact resistance immediately falls and the joint cools off and is finished. The primary coil of such a transformer is generally wound for 110–220 volts while the secondary has only one or two turns and so generates only a few volts; the current capacity of the secondary is, however, very high, as perhaps thousands of amperes are required to make a weld quickly. A small transformer designed for making joints in pieces not more than $\frac{5}{16}''$ diameter is shown in Fig. 196. The jaws, in which the pieces to be welded are clamped, are seen at the top.

*Instrument Transformers.* Instrument transformers are of two types, current and voltage transformers. It is not easy to build an ammeter to carry thousands of amperes, or voltmeters to measure the very high voltages used on transmission lines and so in places where high currents and voltages are to be metered, meters of low ranges are used in connection with suitable instrument transformers. If, for example, the voltage of a 2200-volt line is to be measured, a step-down transformer with a

ratio of 20 : 1 might be used in connection with a **voltmeter** having a range of 125 volts. Such a transformer is called a **potential transformer**; it generally has a full-load capacity of only a few watts, i.e., just sufficient to operate the volt-meter.

In using potential transformers it must be remembered that they will not be accurate if more than the rated load

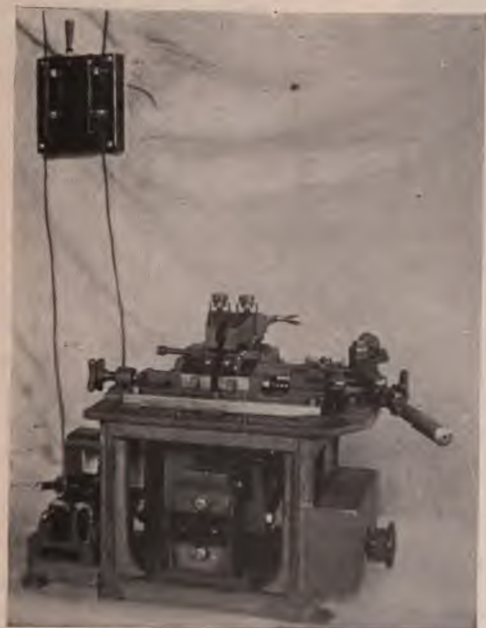


FIG. 196.—A Small Electric Welding Transformer. The transformer proper is located beneath the work holders. Thomson Electric Welding Co.

is taken from them; also, they cannot be used as step-up transformers if accurate results are required, a transformer having a ratio of 60 : 1 stepping down might have a ratio of 1 : 57 when used as a step-up transformer.

The **current transformer** is used when very heavy alter-

nating currents are to be measured. An ammeter to carry 5000 amperes would be very cumbersome and expensive; besides, a five-ampere meter in connection with a current transformer, answers just as well. A current transformer is used also when it is desired to measure the current in a high voltage transmission line. It is not advisable to connect an ammeter directly in series with such a line, so a current transformer is used, and the ammeter, connected in the secondary, is thus insulated from the high tension line. Such a transformer is shown in Fig. 197.

FIG. 197. — Current Transformer for Use in High-tension Transmission line. General Electric Co.

Fig. 198 shows a transformer designed to be connected in series with the station bus-bars to indicate the station current. It has a ratio of 1500 : 5 and a five-ampere ammeter is connected in its secondary circuit. Of course when the meter indicates the full scale deflection (i.e., five amperes on the usual calibration) it signifies that the bus-bars are carrying 1500 amperes and so the full scale of the meter is marked 1500 amperes, etc.

*When a current transformer is carrying current, its secondary circuit must not be opened.* Two bad effects may result, either the transformer may become overheated or else a dangerously high voltage may be generated in the open secondary.

*The Testing Transformer.* All apparatus must be tested for insulation before it is put in use. The voltage used in this test is specified at perhaps twice the normal voltage of the piece of apparatus being tested. Whenever a high-voltage power transformer. for example, is to be tested there must be available for making the test, a transformer which can generate about twice that of the transformer being tested. Also there is required a high voltage for making corona loss tests, tests on the dielectric strength of

FIG. 198.—A Current Transformer for Mounting in the Station Bus-bars. Westinghouse Electric and Mfg. Co.

air, etc. So it is necessary to build transformers (for test purposes only) that can generate between 500,000 and 1,000,000 volts. These test transformers do not have much capacity but they are very bulky because of the space needed for the separation of the coils to give proper insulation.

**78. Polyphase Transformers.** In transforming the voltage of a two- or three-phase power system it is possible to use two or three single-phase transformers, or one polyphase transformer may be used. A two-phase transformer has no commercial importance but three-phase transformers

are used to a considerable extent. If three single-phase, core type transformers were wound each on one leg only and the three empty legs were combined to make the return path for the flux of each transformer we would have essentially a three-phase transformer. The flux carried by the common return path, however, would be zero (because three equal harmonic fluxes 120° apart in time have a zero resultant). Hence as the common return leg carries no flux, it is useless and so may be dispensed with.

FIG. 199.—A Three-phase Transformer Removed from its Tank. General Electric Co.

*Three-phase Transformer.* By this modification the three leg, three-phase transformer is reached, having the primary and secondary windings of one phase on each leg. The design mentioned above, altered slightly to make the core easier to construct, yields a transformer of the form shown in Fig. 199. It may be seen that no common leg is used in such a design.

The three-phase transformer is slightly more efficient than three single-phase transformers as there is less iron per kw. output, but the cost of upkeep and of spare units is greater. In general three single-phase transformers are used because of the greater reliability and flexibility of the installation.

# CHAPTER IX

## THE SYNCHRONOUS MOTOR

**79. Feasibility of Running an Alternator as a Motor.** If two alternating-current generators are operating in parallel on the same bus-bars and the driving power is taken away from one of them, *it will (in general) continue to run, at exactly the same speed it had before the driving power was taken off.*

Suppose two engine-driven generators, operating in parallel, are running at 720 r.p.m. An accurate speed indicating device is put on one of them so that its speed can be read, then the steam is shut off from the engine to which this generator is connected. We would naturally expect the generator to slow down and stop if its driving source is removed but, by watching the speed indicator while the steam is being shut off from the engine, we may see that the alternator not only does not stop but its speed never changes while the steam is being shut off. The speed does not even drop to 719.9 r.p.m. but remains at 720 r.p.m.*

*Reversal of Operation.* Now a machine cannot rotate unless it is being supplied with power, and as the steam engine is delivering no mechanical power it is evident that the machine must be receiving electrical power. Suppose two alternators operating in parallel as shown in Fig. 200 and that the power output of No. 2 is indicated by the wattmeter $W$. It is supposed that $W$ is so connected that when alternator No. 2 is helping No. 1 to carry the load

* This statement holds good only if the speed of the other alternator is held constant during the operation.

it reads *positive power* or *power output*. Now when the steam is shut off from the prime mover of No. 2 it will be noticed that *W* indicates *negative power* or *power input*, that is, *generator No. 2 is running as a motor* and when so running it is styled a **synchronous motor.**

*Speed of Synchronous Motor.* If an alternator is to be used as a synchronous motor it has some features of design different from those of a generator but essentially a synchronous motor is nothing but an alternating current generator operating in a manner opposite to its normal operation. In two respects the synchronous motor and generator are identical; they both have separately excited fields (generally rotating) and they both run at synchronous

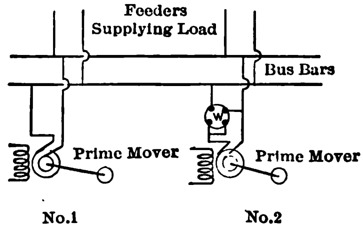



FIG. 200.—Alternators Operating in Parallel.

speed, no matter what the load may be. A 10-pole synchronous motor supplied with 25-cycle power would run 300 r.p.m. no load, 300 r.p.m. half load, and 300 r.p.m. full load, and the same speed even if overloaded. But a 10-pole generator running 300 r.p.m. would generate an e.m.f. of 25 cycles per second, hence the significance of the term "synchronous" motor.

**80. Starting Characteristics.** The synchronous motor may be started by some auxiliary driver and, after being brought up to synchronous speed and proper voltage, it be connected to the line just as though it were an

"incoming" alternator.* The starting device used is generally a small induction motor† (of 5 to 10% the rating of the synchronous motor) mounted on the same shaft with the armature of the synchronous motor.

*Induction Motor as Starter.* The induction motor must have at least one pair of poles less than the synchronous motor or else the synchronous motor could not be brought up to synchronous speed. This is because of the fact that the speed of an induction motor is from 5 to 10% less than synchronous speed. If a 10-pole synchronous motor is to be started by an induction motor this will have only 8 poles. Suppose the power supply is 60 cycles, then the synchronous speed is 720 r.p.m. for a 10-pole machine and 900 r.p.m. for an 8-pole machine. The induction motor would therefore be designed to run at a speed 20% (180 r.p.m.) less than synchronous when it is supplying a load just equal to the *stray power losses* of the synchronous motor. It is always wound for the same voltage and number of phases as the synchronous motor so that the same bus-bars may be used to feed both motors.

*Induction Motor Method of Starting.* Another method of starting is called *the induction motor method.* In this method no extra starting motor is necessary as the synchronous motor itself is made to act as an induction motor. We shall not analyse the theory of the method now as it will be taken up in the chapter on induction motors but it is sufficient to say that *an armature wound with a polyphase winding supplied with polyphase currents generates a rotating magnetic field.* This rotating magnetic field produces eddy currents in the pole faces and damping grids (see next paragraph) and these eddy currents react on the armature to make it revolve. By this action the armature is accelerated until synchronous speed is reached. During

* For a description of the operations necessary to put an incoming alternator on the line see page 262.

† See Chapter X for explanation of induction motor.

the period of acceleration the field of the synchronous motor is left without excitation; after synchronous speed has been reached it is gradually excited and, if the *armature current decreases, the excitation is increased until the normal value is obtained.* It sometimes happens that the armature pulls into synchronism with improper polarity, in which case the *armature current will increase as the field current is increased.* Some method must then be used to pull the armature "into step" (correct polarity), such as re-starting.

*High Starting Current and Low Torque.* The current taken from the line for starting a synchronous motor in this manner is generally two or three times the full-load current, but in spite of this large current the starting torque is not high unless the machine has been properly designed. It was said that this method of starting depended upon the reaction of the eddy currents in the pole faces, but with a laminated pole we know these currents cannot be high because of the subdivision of the path for the eddy currents. To give a fair starting torque in this case it is necessary to put in the pole faces **damping grids** or **amortisseurs.**

*Damping Grids in Pole Faces.* These consist of heavy bars of copper imbedded in slots in the pole face (the direction of the slots is parallel to the armature shaft) and short circuited at their ends by a copper band surrounding the pole. In fact, these grids, cross-bars and band, are sometimes made in one piece, a copper casting. These grids form low-resistance paths for the eddy currents and so help to produce a good starting torque. They also tend to damp out oscillations of the armature (called "hunting")* and from this action they derive their name. In Fig. 201 are shown some poles of a synchronous motor on which the damping grids may be seen.

* See page 327 for explanation of this term.

*below its normal value, it will be noticed that the armature current rapidly increases;* for very low or very high values of the field current the armature current may be much greater than the full-load current although the motor is running light.

*Variation of Armature Current with Field Current.* If the locus of the armature current is plotted, it forms a V-shaped curve, as shown in curve 3 of Fig. 205. If, now, the motor is loaded (mechanically) up to its rating and the field current again carried through as wide a range as

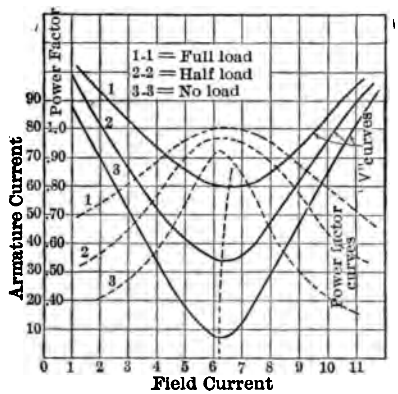



FIG. 205.—Phase Characteristics or "V" Curves of a Synchronous Motor.

possible, curve 1 will be obtained. For half load, a curve similar to that one numbered 2 would be obtained. These curves, showing the relation between the armature current and the field current for a fixed load are called the **phase characteristics** or "V" curves of the synchronous motor.

*Variation of Power Factor with Field Current.* If the power input were measured as well as the armature current, the power-factor could be calculated, the line voltage being known. For the different loads the power-factor curves would resemble those shown in dotted lines in Fig. 205.

*Low-voltage Taps for Starting.* In starting a motor by the induction method it is not feasible to connect it, when stationary, to the line of normal voltage because the starting current would be so excessive (from 5 to 10 times the rated current) that the armature winding might be injured. So the transformers feeding the motor are usually fitted with half voltage taps and power is taken from these taps to the lower sides of a double-throw switch, to the blades of which the motor armature is connected as in Fig. 202. The starting switch is thrown down at first and held there until the motor approaches synchronous speed, when it is

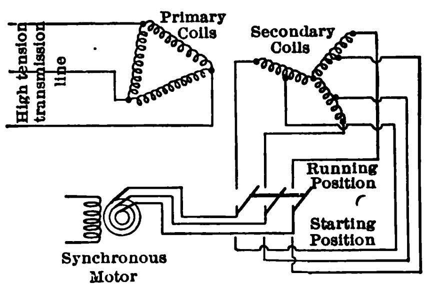



Fig. 202.—Connection of a Synchronous Motor to Half-voltage Taps for Starting.

quickly thrown to its upper position, which is the running position.

*Excitation.* Of course the field circuit of a synchronous motor requires continuous current. As the a-c. line feeding the motor cannot furnish the current for excitation some separate source of c-c. power is required. Sometimes a small c-c. self-exciting generator is mounted on the armature shaft of the synchronous motor as shown in Fig. 203; the output of this small c-c. generator is just sufficient to supply the power for the field circuit of the synchronous motor, perhaps 3% of the rating of the motor.

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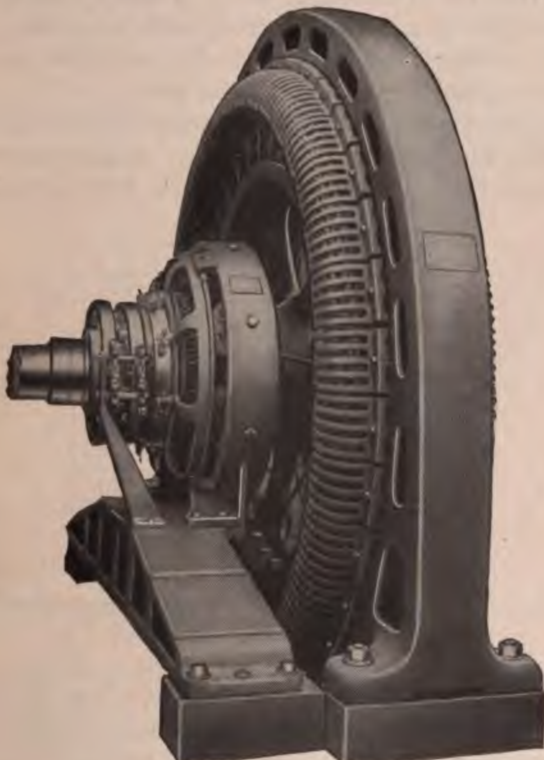

FIG. 203.—A Synchronous Machine with Exciter on same Shaft.

heavy current will rush through the armature. This causes the circuit breakers to open and the motor is cut off from the supply line and stops. It must then be re-started and synchronized as described in a previous paragraph. That overload at which the motor falls out of synchronism

is called the "pull-out" point; generally this is between 75 and 150% overload.

*Use of Synchronous Motors.* Speed-load curves for two motors are given in Fig. 204. The shape of these curves shows that the synchronous motor is entirely unsuited for loads requiring a variable speed, such as railway work, or for driving machine tools. Its principal use is in frequency-changing motor-generator sets.

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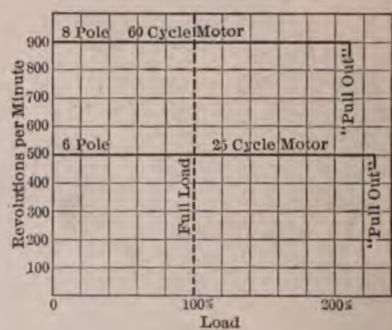


FIG. 204.—Speed-load Curves for Synchronous Motors.

which furnishes power to local lighting circuits. This transformation is necessary because 25 cycles per second is too low to use for lamps as bad flickering results. The synchronous motors of these sets are also used to regulate the power factor of the transmission line, as described in a later paragraph.

**82. Phase Characteristics or "V" Curves.** Suppose a synchronous motor is running light and that the field current is at its normal value; the armature current will be quite small, in fact, just enough to supply the no-load losses. *If, now, the field current is altered, either above or*

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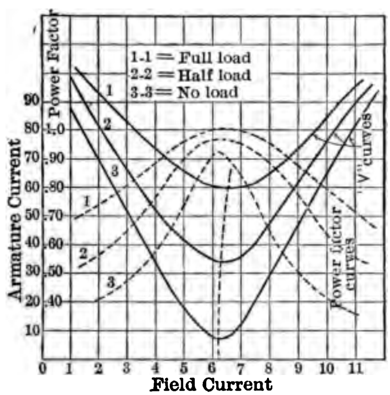


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From these curves it may be seen that although a variation in the field current (from normal) is accompanied by an increase of the armature current, the *power input* to the motor is practically unaltered because of the decreased power factor.

*Reactive Current Caused by Improper Field Current.* We must conclude that field currents other than normal cause, in the armature circuit, either a leading or a lagging current, the amount of lead or lag depending upon how much the field has been changed from its normal value. If a power-factor meter had been used in the V curve test, it would have indicated that, with fields *greater* than normal, the motor took a *leading* current from the line, while with *less* than normal excitation the motor took a *lagging* current from the line. This idea is generally expressed by saying that *an overexcited synchronous motor draws a leading current and an underexcited motor a lagging current.*

*Reason for Reactive Current.* The reason for these facts becomes apparent when we consider the circuit made up of the synchronous motor armature, the line, and the armature of the generator supplying the line, as shown in Fig. 206. $E_g$ represents the generator voltage and $E_m$ the e.m.f. *generated in the armature of the motor.* Any current which flows in this circuit must then be caused by the resultant of $E_m$ and $E_g$.

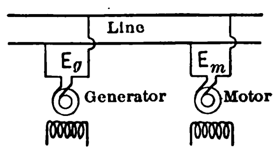


FIG. 206.—Circuit Made up of Generator Armature, Motor Armature and Line.

In Fig. 207 are shown the possible relations of these vectors. First, assuming no load and neglecting the stray power, we see that when $E_m$ and $E_g$ are equal and opposite the resultant e.m.f. in the circuit in zero, hence no current will flow. But now suppose the motor is overexcited so that the motor voltage is shown by $OE_m'$ in Fig. 207. The

## CHAPTER IX

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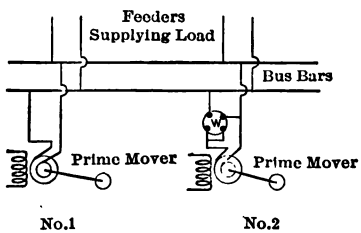


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* For a description of the operations necessary to put an incoming alternator on the line see page 262.

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resultant of $OE_m'$ and $OE_g$ is $OR'$. This resultant voltage will cause a current to flow (through the two armatures and line) which will lag nearly 90° behind $OR'$ as the armatures are highly inductive. This current is shown at $OI'$ in Fig. 207. This current is mostly reactive and it *leads the line voltage,* $OE_g$. Now if the motor voltage is decreased to $OE_m''$ the resultant voltage becomes $OR''$ and the current through the circuit $OI''$. This again is reactive current and it *lags behind the line voltage,* $OE_g$.

*Power Factor Depends Upon Load and Field Current.* When the motor is already drawing from the line an active

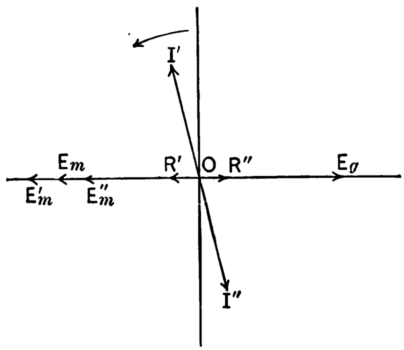
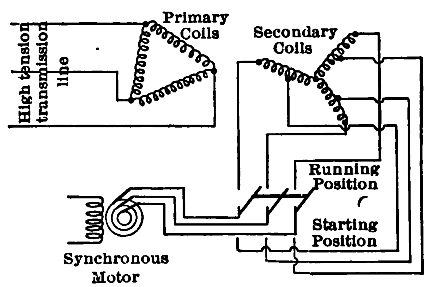



FIG. 207.—Effect of Increasing or Decreasing the Field Current of the Synchronous Motor.

current (to supply the power for whatever load it is carrying) and the field current is varied, then the total armature current is made up of the active current and the reactive current; the resultant power factor depends upon the relative magnitudes of the two. This fact accounts for the results given in Fig. 205 which show higher power factors for the full-load run and half-load run than for the no-load run.

At light loads it is sometimes impossible to make the power factor equal to unity, no matter how the field current

*Low-voltage Taps for Starting.* In starting a motor by the induction method it is not feasible to connect it, when stationary, to the line of normal voltage because the starting current would be so excessive (from 5 to 10 times the rated current) that the armature winding might be injured. So the transformers feeding the motor are usually fitted with half voltage taps and power is taken from these taps to the lower sides of a double-throw switch, to the blades of which the motor armature is connected as in Fig. 202. The starting switch is thrown down at first and held there until the motor approaches synchronous speed, when it is

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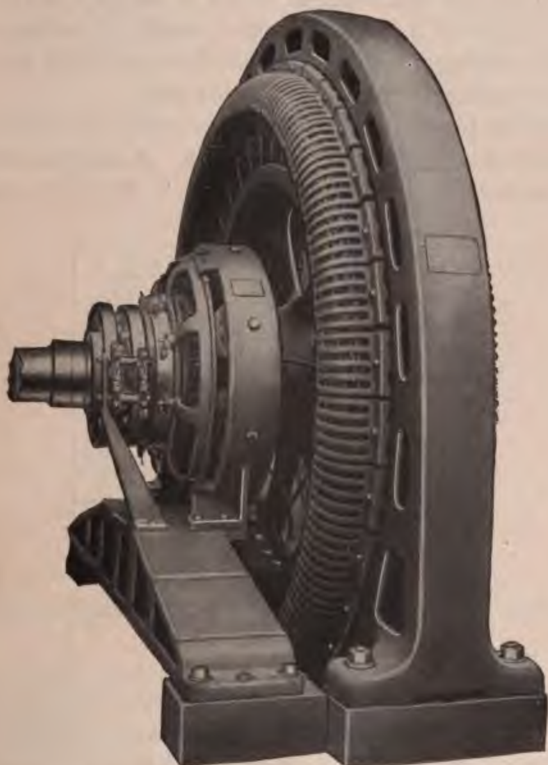

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is called the "pull-out" point; generally this is between 75 and 150% overload.

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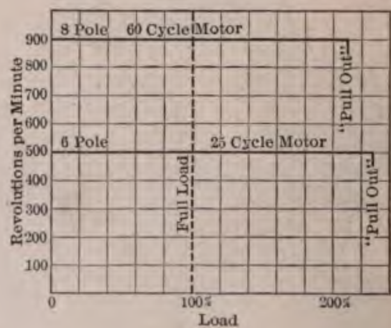


FIG. 204.—Speed-load Curves for Synchronous Motors.

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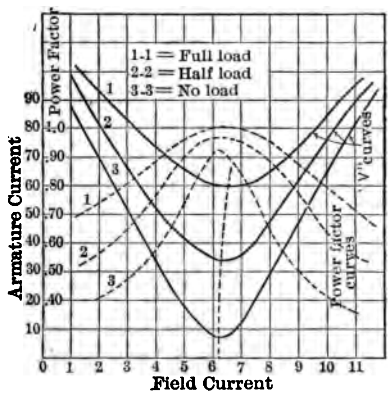


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*Variation of Power Factor with Field Current.* If the power input were measured as well as the armature current, the power-factor could be calculated, the line voltage being known. For the different loads the power-factor curves would resemble those shown in dotted lines in Fig. 205.

will merely " float " on the line, with its field considerably overexcited. In such case it is called a **synchronous condenser.**

*Vector Diagram of the Circuit.* Fig. 211 illustrates the operation of such a scheme. The current $I'$ lags behind

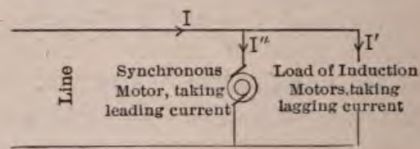


FIG. 211.—Connection of Synchronous Motor to Compensate for the Lagging Current of an Induction Motor Load.

the line voltage and the current $I''$ is ahead of the line voltage. Evidently under proper conditions the line current $I$ may be in phase with the line voltage.

The vector relations in such a case are shown in Fig. 212. The current supplied to the induction motor is shown at $OI'$, having the active component $OD$ and the reactive component, $OA$. The synchronous condenser current is shown at $OI''$, having an active component $OC$, just sufficient to supply its own losses. The field has been overexcited to such an extent that its leading component $OB$ is just equal to $OA$. Evidently the line current $OI$ will be in phase with the line voltage $OE$, hence the line power will be unity and the line carrying capacity as great as is possible.

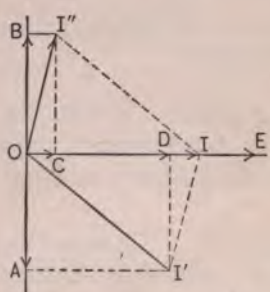


FIG. 212.—Vector Diagram of Currents, Showing how the Combined Load May have a Power Factor of Unity.

It is not generally attempted to bring the power factor of the line up to unity; this scheme of using a synchronous

# CHAPTER IX

## THE SYNCHRONOUS MOTOR

**79. Feasibility of Running an Alternator as a Motor.** If two alternating-current generators are operating in parallel on the same bus-bars and the driving power is taken away from one of them, *it will (in general) continue to run, at exactly the same speed it had before the driving power was taken off.*

Suppose two engine-driven generators, operating in parallel, are running at 720 r.p.m. An accurate speed indicating device is put on one of them so that its speed can be read, then the steam is shut off from the engine to which this generator is connected. We would naturally expect the generator to slow down and stop if its driving source is removed but, by watching the speed indicator while the steam is being shut off from the engine, we may see that the alternator not only does not stop but its speed never changes while the steam is being shut off. The speed does not even drop to 719.9 r.p.m. but remains at 720 r.p.m.*

*Reversal of Operation.* Now a machine cannot rotate unless it is being supplied with power, and as the steam engine is delivering no mechanical power it is evident that the machine must be receiving electrical power. Suppose two alternators operating in parallel as shown in Fig. 200 and that the power output of No. 2 is indicated by the wattmeter $W$. It is supposed that $W$ is so connected that when alternator No. 2 is helping No. 1 to carry the load

* This statement holds good only if the speed of the other alternator is held constant during the operation.

it reads *positive power* or *power output*. Now when the steam is shut off from the prime mover of No. 2 it will be noticed that *W* indicates *negative power* or *power input*, that is, *generator No. 2 is running as a motor* and when so running it is styled a **synchronous motor.**

*Speed of Synchronous Motor.* If an alternator is to be used as a synchronous motor it has some features of design different from those of a generator but essentially a synchronous motor is nothing but an alternating current generator operating in a manner opposite to its normal operation. In two respects the synchronous motor and generator are identical; they both have separately excited fields (generally rotating) and they both run at synchronous

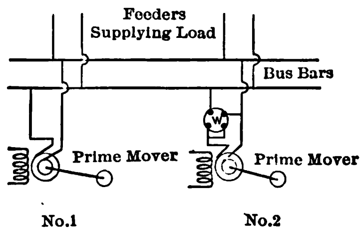


FIG. 200.—Alternators Operating in Parallel.

speed, no matter what the load may be. A 10-pole synchronous motor supplied with 25-cycle power would run 300 r.p.m. no load, 300 r.p.m. half load, and 300 r.p.m. full load, and the same speed even if overloaded. But a 10-pole generator running 300 r.p.m. would generate an e.m.f. of 25 cycles per second, hence the significance of the term " synchronous " motor.

**80. Starting Characteristics.** The synchronous motor may be started by some auxiliary driver and, after being brought up to synchronous speed and proper voltage, it may be connected to the line just as though it were an

"incoming" alternator.* The starting device used is generally a small induction motor† (of 5 to 10% the rating of the synchronous motor) mounted on the same shaft with the armature of the synchronous motor.

*Induction Motor as Starter.* The induction motor must have at least one pair of poles less than the synchronous motor or else the synchronous motor could not be brought up to synchronous speed. This is because of the fact that the speed of an induction motor is from 5 to 10% less than synchronous speed. If a 10-pole synchronous motor is to be started by an induction motor this will have only 8 poles. Suppose the power supply is 60 cycles, then the synchronous speed is 720 r.p.m. for a 10-pole machine and 900 r.p.m. for an 8-pole machine. The induction motor would therefore be designed to run at a speed 20% (180 r.p.m.) less than synchronous when it is supplying a load just equal to the *stray power losses* of the synchronous motor. It is always wound for the same voltage and number of phases as the synchronous motor so that the same bus-bars may be used to feed both motors.

*Induction Motor Method of Starting.* Another method of starting is called *the induction motor method.* In this method no extra starting motor is necessary as the synchronous motor itself is made to act as an induction motor. We shall not analyse the theory of the method now as it will be taken up in the chapter on induction motors but it is sufficient to say that *an armature wound with a polyphase winding supplied with polyphase currents generates a rotating magnetic field.* This rotating magnetic field produces eddy currents in the pole faces and damping grids (see next paragraph) and these eddy currents react on the armature to make it revolve. By this action the armature is accelerated until synchronous speed is reached. During

* For a description of the operations necessary to put an incoming alternator on the line see page 262.

† See Chapter X for explanation of induction motor.

the period of acceleration the field of the synchronous motor is left without excitation; after synchronous speed has been reached it is gradually excited and, if the *armature current decreases, the excitation is increased until the normal value is obtained.* It sometimes happens that the armature pulls into synchronism with improper polarity, in which case the *armature current will increase as the field current is increased.* Some method must then be used to pull the armature "into step" (correct polarity), such as re-starting.

*High Starting Current and Low Torque.* The current taken from the line for starting a synchronous motor in this manner is generally two or three times the full-load current, but in spite of this large current the starting torque is not high unless the machine has been properly designed. It was said that this method of starting depended upon the reaction of the eddy currents in the pole faces, but with a laminated pole we know these currents cannot be high because of the subdivision of the path for the eddy currents. To give a fair starting torque in this case it is necessary to put in the pole faces **damping grids** or **amortisseurs.**

*Damping Grids in Pole Faces.* These consist of heavy bars of copper imbedded in slots in the pole face (the direction of the slots is parallel to the armature shaft) and short circuited at their ends by a copper band surrounding the pole. In fact, these grids, cross-bars and band, are sometimes made in one piece, a copper casting. These grids form low-resistance paths for the eddy currents and so help to produce a good starting torque. They also tend to damp out oscillations of the armature (called "hunting")* and from this action they derive their name. In Fig. 201 are shown some poles of a synchronous motor on which the damping grids may be seen.

* See page 327 for explanation of this term.

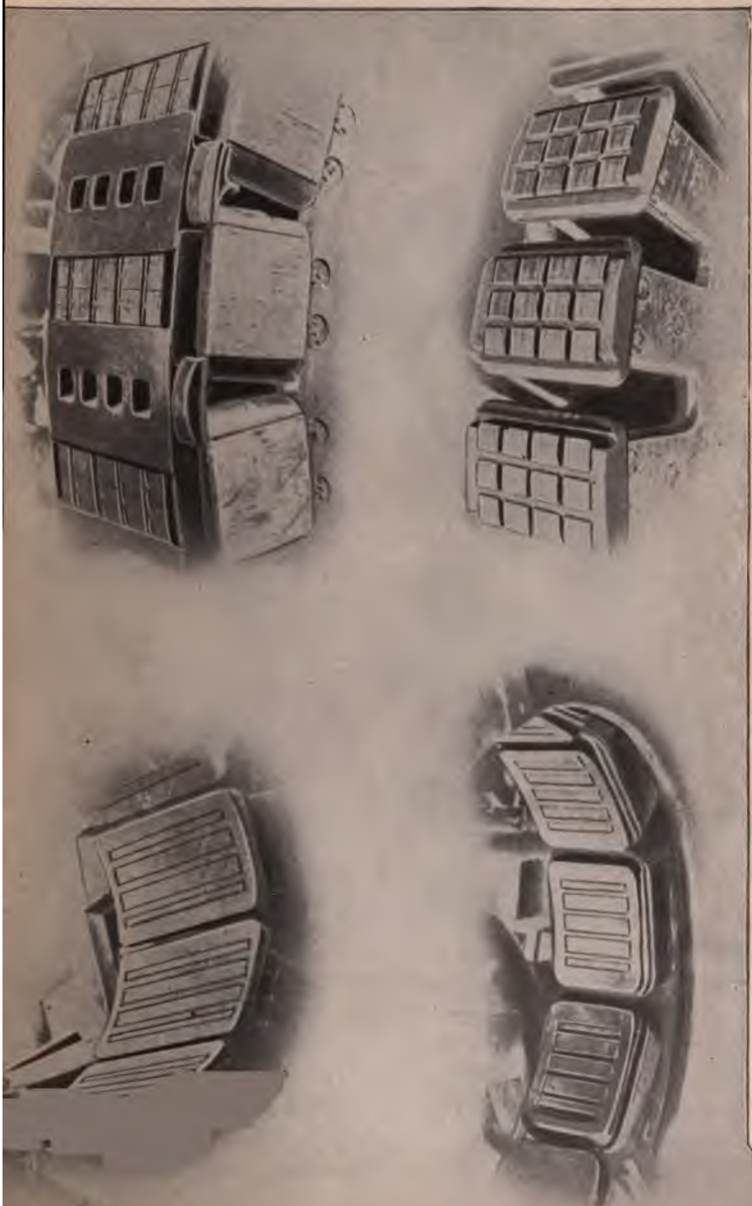

Fig. 201.—Field Structure of a Synchronous Machine, Showing Different Types of Damping Grids
Westinghouse Electric and Mfg. Co.

*Low-voltage Taps for Starting.* In starting a motor by the induction method it is not feasible to connect it, when stationary, to the line of normal voltage because the starting current would be so excessive (from 5 to 10 times the rated current) that the armature winding might be injured. So the transformers feeding the motor are usually fitted with half voltage taps and power is taken from these taps to the lower sides of a double-throw switch, to the blades of which the motor armature is connected as in Fig. 202. The starting switch is thrown down at first and held there until the motor approaches synchronous speed, when it is

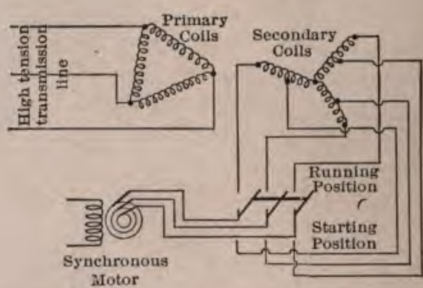


FIG. 202.—Connection of a Synchronous Motor to Half-voltage Taps for Starting.

quickly thrown to its upper position, which is the running position.

*Excitation.* Of course the field circuit of a synchronous motor requires continuous current. As the a-c. line feeding the motor cannot furnish the current for excitation some separate source of c-c. power is required. Sometimes a small c-c. self-exciting generator is mounted on the armature shaft of the synchronous motor as shown in Fig. 203; the output of this small c-c. generator is just sufficient to supply the power for the field circuit of the synchronous motor, perhaps 3% of the rating of the motor.

**81. Speed-load Curves.** The speed of a synchronous motor is absolutely constant throughout its range of operation. If an excessive overload is put on the motor, it will pull out of synchronism with the line and a very

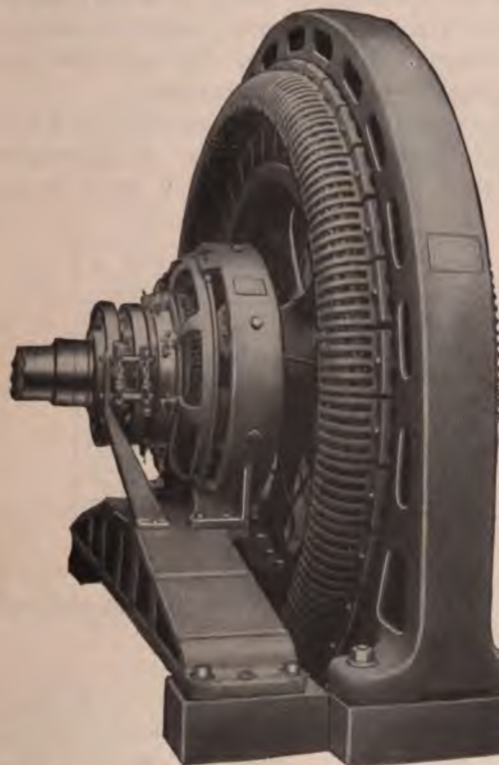

FIG. 203.—A Synchronous Machine with Exciter on same Shaft.

heavy current will rush through the armature. This causes the circuit breakers to open and the motor is cut off from the supply line and stops. It must then be re-started and synchronized as described in a previous paragraph. That overload at which the motor falls out of synchronism

is called the "pull-out" point; generally this is between 75 and 150% overload.

*Use of Synchronous Motors.* Speed-load curves for two motors are given in Fig. 204. The shape of these curves shows that the synchronous motor is entirely unsuited for loads requiring a variable speed, such as railway work, or for driving machine tools. Its principal use is in frequency-changing motor-generator sets.

Such motor-generator sets are generally used in connection with 25-cycle transmission lines. A 25-cycle synchronous motor is direct connected to a 60-cycle generator

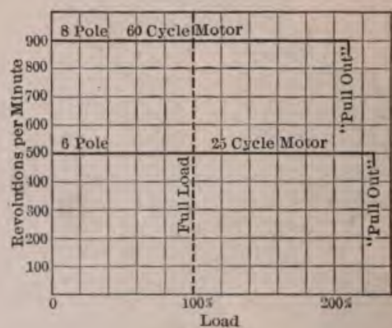


FIG. 204.—Speed-load Curves for Synchronous Motors.

which furnishes power to local lighting circuits. This transformation is necessary because 25 cycles per second is too low to use for lamps as bad flickering results. The synchronous motors of these sets are also used to regulate the power factor of the transmission line, as described in a later paragraph.

**82. Phase Characteristics or "V" Curves.** Suppose a synchronous motor is running light and that the field current is at its normal value; the armature current will be quite small, in fact, just enough to supply the no-load losses. *If, now, the field current is altered, either above or*

*below its normal value, it will be noticed that the armature current rapidly increases;* for very low or very high values of the field current the armature current may be much greater than the full-load current although the motor is running light.

*Variation of Armature Current with Field Current.* If the locus of the armature current is plotted, it forms a V-shaped curve, as shown in curve 3 of Fig. 205. If, now, the motor is loaded (mechanically) up to its rating and the field current again carried through as wide a range as

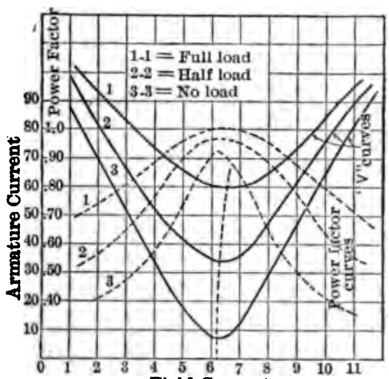


FIG. 205.—Phase Characteristics or "V" Curves of a Synchronous Motor.

possible, curve 1 will be obtained. For half load, a curve similar to that one numbered 2 would be obtained. These curves, showing the relation between the armature current and the field current for a fixed load are called the **phase characteristics** or "V" curves of the synchronous motor.

*Variation of Power Factor with Field Current.* If the power input were measured as well as the armature current, the power-factor could be calculated, the line voltage being known. For the different loads the power-factor curves would resemble those shown in dotted lines in Fig. 205.

current because $I_2$ is a maximum at the time $t_1$; suppose the polarity is as shown, there being a $N$ pole at 2 and a $S$ pole at 4. Then, at the time $t_1$, the magnetic field is in the condition shown on the circle marked $t_1$ in Fig. 218. At a time $t_2$ (Fig. 217) the current $I_1$ is a maximum and $I_2$ has a zero value; poles 1 and 3 are therefore magnetized while poles 2 and 4 now have zero magnetism. This gives a field as shown in the circle marked $t_2$ in Fig. 218.

At a time $t_3$ windings 1 and 3 carry no current and windings 2 and 4 carry a maximum current, but this current

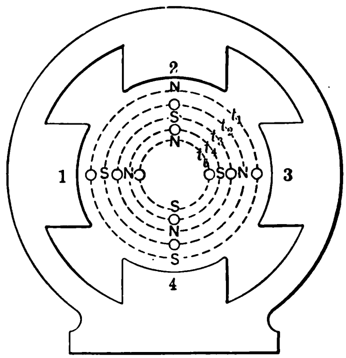


FIG. 218.—Polarity of the Different Poles at Successive Instants.

is in the opposite direction to what it was at the time $t_1$. Hence the magnetic field is as shown on the third circle of Fig. 218, marked $t_3$. At a time $t_4$ poles 1 and 3 are magnetized but in the opposite direction to what they were at the time $t_2$, and poles 2 and 4 have no magnetism. This condition is shown on the circle $t_4$. At a time $t_5$ the magnetic field is in the same direction as it was at the time $t_1$, and after $t_5$ the previous cycle is repeated.

*Combination of Fields Equivalent to a Rotating Field.* This succession of conditions in the magnetic circuit is evidently equivalent to a *rotating magnetic field;* this may be

seen from Fig. 219 which shows the direction of the fields given in Fig. 218.

*Action of any Polyphase Winding.* A three-phase winding, supplied with three-phase power would give a rotating field in exactly the same manner as has just been described for the two-phase winding. In fact, any polyphase winding connected with a suitable polyphase power supply generates a rotating magnetic field, which remains constant in strength as it rotates.

**91. Speed of Rotation of the Field.** By referring to Figs. 218 and 219, it is seen that, in one cycle of current, the magnetic field travels from pole 1 all the way around the stator and back to pole 1. If we had represented a

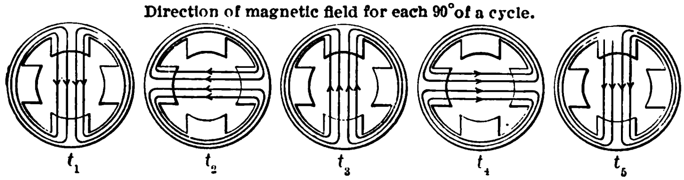


FIG. 219.—Direction of Magnetic Field at Successive Instants.

stator having *two pairs of poles per phase,* an analysis of the rotating field would have shown that it moves *half way around the stator* in the time required for one cycle of the current. It is seen that the magnetic field travels over *one pair of poles per phase for one cycle of current,* and this irrespective of the number of poles or phases. A two-phase motor having four poles per phase requires two cycles of current for a complete revolution of the magnetic field; this holds true whether the motor is two-phase, three-phase, or any number of phases.

*Calculation of the Speed of the Field.* When it is stated that an induction motor has four poles, four poles per phase is always meant. A four-pole, three-phase motor, for example, would actually have twelve coils (or sets of coils).

How fast will the magnetic field revolve in such a motor if it is supplied with 60-cycle power? As the motor has *two pairs* of poles per phase, it requires two cycles of current to make the field travel all the way around the stator. As there are 60 cycles per second the field will make $60 \div 2 \times 60$, or 1800 r.p.m. Suppose an 8-pole motor supplied with 25-cycle power; it would require 4 cycles of current to give the magnetic field one complete revolution, hence the field would turn $25 \div 4 \times 60$ or 375 r.p.m.

*Rotor Speed Less than that of the Field.* The speed at which the field of an induction motor turns is called **synchronous speed.** The rotor never turns as fast as the magnetic field, but perhaps 5–10% slower.

*Slip.* The difference between rotor speed and field speed is termed the **slip.** Slip is generally expressed as a per cent of the synchronous speed.

Thus slip (%) = {synchronous speed − rotor speed) ÷ synchronous speed} × 100. . . . . . . . . . . (76)

Suppose a 60-cycle, 16-pole, 3-phase motor has a slip at full load of 6%; at what speed does the rotor turn at full load?

| | |
|---|---|
| Synchronous speed | = 450 r.p.m.; |
| Slip | = 450 × 6% = 27 r.p.m.; |
| Rotor speed | = 450 − 27 = 423 r.p.m. |

**92. Rotor Construction.** There are two types of rotor, one called the **squirrel-cage rotor** and the other the **wound rotor.** The cores of both must, of course, be of laminated iron; the distinction comes from the manner in which the conductors of the rotor winding are connected together.

*Squirrel-cage Rotor.* In the squirrel-cage rotor the winding consists of heavy copper bars imbedded in slots in the periphery of the rotor and *these copper bars are all short circuited* at both ends of the rotor by being soldered to

heavy copper rings. The rotor slots are always semi-closed (see p. 46) so that the bars must be pushed in from the ends of the rotor core. As the voltage generated in such a winding is low, very little insulation is required on the bars; in fact, a heavy coat of insulating enamel generally proves sufficient.

An illustration of a squirrel-cage rotor, showing the bars and short-circuiting ring is given in Fig. 220. The

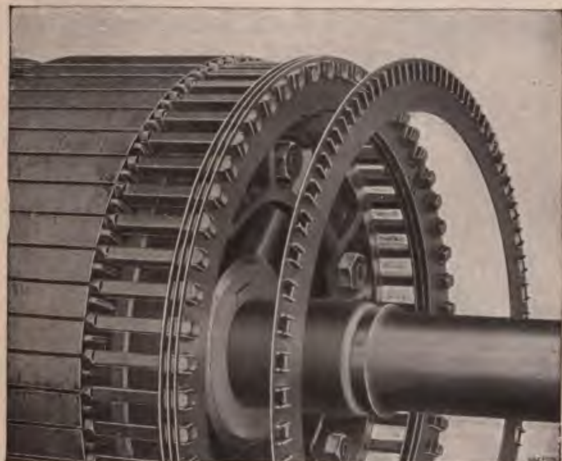

Fig. 220.—View of End Rings and Bars of a Squirrel-cage Rotor, to Show the Style of Winding. General Electric Co.

bars are not always placed parallel to the shaft, but are sometimes "skewed" to some extent. This skewing tends to give a more uniform torque in starting and also to reduce the humming noise made when the machine is running.

*Wound Rotor.* The wound rotor is equipped with a winding very similar to that of a revolving-armature alternator. The different conductors are insulated from one another and arranged in coils. These coils are generally

to 109 volts. Such a fluctuation in the line voltage is prohibitive if lamps are connected to the line and even if there is no lamp load to suffer, synchronous motors or synchronous converters are likely to be disturbed in their operation and may even pull out of step if the fluctuation is excessive.

*Low-starting Torque.* In addition to these bad features of the squirrel-cage rotor, we have the additional one that *the starting torque is very small,* generally but a small fraction of the full-load torque.

*Rotor Circuit with Variable Resistance.* A high-resistance rotor would have, when starting, none of the bad features

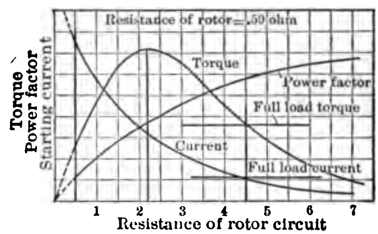


FIG. 223.—Curves Showing the Effect upon the Starting Characteristics of Varying the Resistance in the Rotor Circuit.

mentioned above, but the efficiency of a motor with a high-resistance rotor is necessarily low and the speed regulation is poor. The effect of rotor resistance upon the starting characteristics of a motor is shown in Fig. 223. These curves were obtained by a laboratory test of a small motor having a wound rotor. Various resistances were inserted in the external circuit of the rotor and the different quantities measured. The rotor itself had a resistance of .5 ohm, so that the quantities could not be measured for a rotor circuit resistance less than this, but the curves were extrapolated, as shown by the dotted lines.

*Effect of Rotor Resistance upon Starting Characteristics.* It is seen from these results that, as external resistance is

resistance of the rotor circuit can be controlled by varying the resistance of this external circuit. This is done through a controller switch similar in appearance and construction to the railway controller.

The resistance may sometimes be located inside of the rotor itself, on the spider. In such a rotor no slip rings are necessary; the ends of the rotor windings are connected to sliding fingers which make contact with the resistance. The position of these fingers controls the amount of resistance in the rotor circuit and the position of the fingers is regulated by a lever which operates a sliding sleeve mounted on the rotor shaft.

The three types of rotor are shown in Fig. 221; the brush rigging for the slip ring rotor is also shown.

For induction motors of less than five horsepower, the squirrel-cage rotor is nearly always used; it may be used in sizes as large as 150 or 200 h.p. For larger sized motors the wound rotor with external resistance, is generally used for reasons given in the succeeding paragraphs.

**93. Development of Torque.** Consider a squirrel-cage rotor in a revolving magnetic field. A cross-section of the magnetic field and rotor conductors is shown in Fig. 222. A two-pole motor is represented and it is supposed that the field turns counterclockwise. If the rotor is stationary (or turning at any speed less than that of the field) the conductors on the top of the rotor will have a positive e.m.f. induced in them (into the paper in the figure) and those on the bottom will have a negative e.m.f. (out of the paper in the figure). And as the rotor conductors are all connected together by the end rings, currents will flow in the rotor in the same direction as these e.m.fs. so that the top conductors carry current toward the reader and the bottom conductors carry current away from the reader.

*All Conductors give Torque in the Same Direction.* But we know that a conductor carrying current in a magnetic field is acted on by a force which tends to move the con-

10% of synchronous speed. The difference between the field speed and the rotor speed (i.e., the slip) increases rapidly with overloads and, if the motor is loaded too much, it stops altogether and is said to be "stalled." Under such conditions the circuit breakers (or fuses) in series with the motor open the circuit and the load must be removed, the circuit closed, and the motor again started. This maximum load point is generally 75 or 100% greater than the rated load of the motor; it varies with different motors, but should always be considerably greater than the

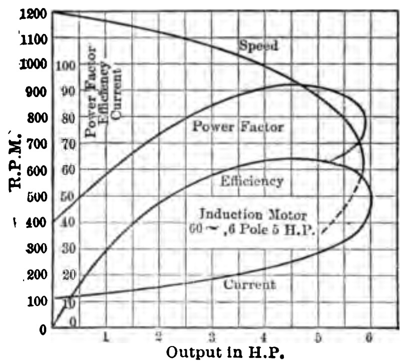


FIG. 225.—Same as Shown in Fig. 224 but Some Resistance has been Added to the Rotor Circuit.

rated load, otherwise the motor is likely to be "stalled" frequently.

**97. Effect of Rotor Resistance upon Operating Characteristics.** The motor whose characteristics are shown in Fig. 224 was equipped with a slip-ring rotor. For the purposes of the test the rotor circuit resistance was increased by inserting extra resistance between the brushes on the slip rings and the motor characteristics were again obtained. The results are given in Fig. 225. They show that an *increase* in rotor resistance produces, for a given load, an

and hence the rotor can speed up no more. It follows, therefore, that the limiting speed for the rotor is the same as the speed of rotation of the magnetic field.

*Actual Rotor Speed always Less than that of the Field.* Actually, there is always some friction for the rotor to overcome, and hence the rotor can never run at exactly synchronous speed (i.e., the speed of the field), but it approximates it very closely. In a certain motor having a synchronous speed of 900 r.p.m. the rotor turned 898 r.p.m. at no load, or, we might say, the rotor had a slip of 2 r.p.m. or about 0.2%.

**95. Starting Characteristics.** The three important characteristics of an induction motor when starting are torque, current, and power factor. When at rest an induction motor with a short-circuited rotor is essentially a short-circuited transformer, the rotor corresponding to the short-circuited secondary and the stator to the primary winding. We know that a short-circuited transformer draws from the circuit, to which it is connected, a very heavy current, and this is also true of a squirrel-cage induction motor, when at rest.

*Large Starting Current.* The first bad feature of a low-resistance squirrel-cage rotor then is *the large starting current;* a certain 5 h.p. motor having a full-load current of 27.5 amperes, takes 130 amperes when first connected to the supply line of normal voltage and larger squirrel-cage motors draw a proportionately greater overload current when starting.

*The Power Factor is Low.* The power factor of this starting current is very low and this, combined with the fact that the current is large, produces bad fluctuations in the line voltage when such a motor is switched to the supply line. The 5-h.p. motor mentioned above caused the line voltage to drop from 110 volts to 102 volts when starting, although when taking its normal full-load current and running at its normal speed, the line voltage held up

the rotor always turns with a speed somewhat less than that of the revolving field and that the speed of rotation of the field is determined by the frequency of the power supply. A motor designed for 25 cycles will run at more than twice its rated speed if connected to a 60-cycle line. In fact the speed of the motor is practically proportonal to the frequency of the power supply.

A motor designed for a low frequency can safely be run on higher frequency lines, provided the mechanical strains in the rotor are not dangerous at the higher speed. But a motor designed for 60 cycles should never be operated on a 25-cycle line because of the excessive densities resulting in the magnetic circuit and the corresponding high hysteresis loss. The multiple frequency scheme for speed control never came into prominence owing probably to the complexity of the wiring and station apparatus.

*Varying the Number of Poles.* In another scheme for speed control the windings of the stator are connected through a series of switches; by proper operation of these switches it is possible to change the number of poles on the stator. Thus a motor might have its windings so connected through these switches that when they are thrown one way the motor has eight poles and when thrown in the opposite way the motor might have six poles. This scheme, while it gives an efficient speed control, requires rather complicated connections on the coils and so is not used as yet to a great extent.

*Cascade Connection.* In some installations (notably railway equipment) two motors are used connected in concatenation or cascade. The stator of the first motor is connected to the line, the slip rings of the first rotor are connected to the stator windings of the second, and the second rotor circuit is closed through a variable resistance. When all the resistance is cut out of rotor No. 2, both motors operate at half the speed they would have if directly connected to the line (with rotor short circuited). This

added to the rotor circuit, the torque and the power factor increase, while the current decreases. A certain external resistance (in Fig. 223 this is 2.2 ohms) gives a maximum starting torque; if more than this is inserted the torque again falls off. The proper starting resistance for this motor would be about 3 ohms; for this resistance the torque is still fairly high, the power factor is comparatively high, and the current is not much in excess of the full-load current.

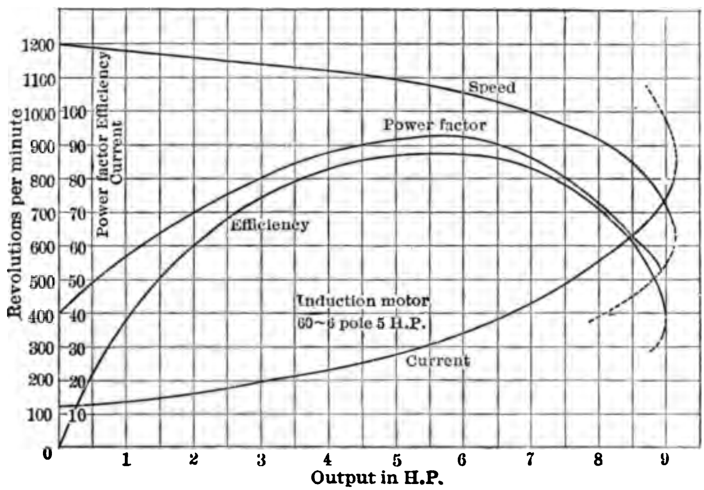


**Fig. 224.**—Running Characteristics of a Small Wound-rotor Induction Motor, Having No External Resistance.

**96. Running Characteristics.** The running characteristics of the ordinary small induction motor with a low-resistance rotor are shown by the curves of Fig. 224. The no-load current (called the "running-light" current) is generally between 20 and 40% of the full-load current. The current increases with increase of load, and increases more rapidly for the overloads.

The speed falls off slightly as the load increases, the decrease from no load to full load being generally less than

carry much current, there is an additional winding at right angles to this, which is designed of sufficient size to carry a magnetizing current during the starting period only. After the rotor approaches synchronous speed this additional winding is automatically cut out of the circuit. Fig. 226 shows the connection for such a split-phase motor; the auxiliary coil is connected to the single-phase supply line *through a condenser*. This condenser, if large enough, will make the current in the auxiliary coil lead the current in the main coil by nearly 90°, hence the two coils act like the two coils of a two-phase motor and produce a rotating

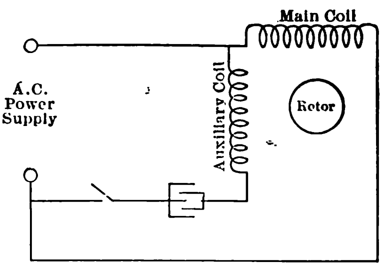


Fig. 226.—Connection for a Split-phase, Single-phase Induction Motor, using Condenser to Get the Out-of-phase Current in the Starting Coil.

magnetic field. After a suitable speed has been reached, the auxiliary circuit is opened to prevent overheating. An inductance may be used instead of a condenser to bring about the phase difference of the currents in the two windings.

*Commutator Type of Motor.* Another type of single-phase induction motor which is much used employs a rotor fitted with a commutator and brushes quite similar to a continuous-current motor. After the motor reaches the proper speed, all of the commutator bars are automatically short-circuited and the brushes lifted from the commutator. This action changes the rotor to an ordinary squirrel-cage

increased slip, a decreased efficiency, and an increase in current. Also, the maximum load obtainable from the motor is now only 6 hp., whereas with no extra resistance it was nearly 10 hp.

If still more resistance were added to the rotor circuit, the speed and efficiency for a given output would be still further decreased. If too much resistance is put in the rotor circuit, very little output can be obtained from it; *practically all of the power which goes into the stator of the motor is used up as heat in the rotor circuit resistance grids.*

By using a motor with a wound rotor and inserting external resistance, it is possible to obtain good starting characteristics, i.e., low current, high torque and power factor. As the rotor speeds up the external resistance is gradually cut out, and the motor is normally operated with no external resistance in the rotor circuit. Thus the running characteristics are similar to those of the squirrel-cage motor and the starting characteristics are much better than those of the squirrel-cage rotor.

**98. Speed Control.** Several methods have been designed for varying the speed of an induction motor for a given output but none of them are very successful; the induction motor is essentially a constant speed motor.

*Variation of Rotor Circuit Resistance.* The first method consists of inserting resistance in the rotor circuit. We explained in the last paragraph that this will cut down the rotor speed, for a given load, but that it results also in a low efficiency and a low "pull out" point. Hence the rotor-resistance control scheme can be used economically only during the time the motor is being started; in this way it is similar to the resistance used for the control of series c-c. railway motors.

*Power Supply of Several Frequencies.* It was at one time thought feasible to have lines of two or three frequencies and to switch the motor from one line to the other as a change in speed might be desired. We have shown that

the rotor always turns with a speed somewhat less than that of the revolving field and that the speed of rotation of the field is determined by the frequency of the power supply. A motor designed for 25 cycles will run at more than twice its rated speed if connected to a 60-cycle line. In fact the speed of the motor is practically proportonal to the frequency of the power supply.

A motor designed for a low frequency can safely be run on higher frequency lines, provided the mechanical strains in the rotor are not dangerous at the higher speed. But a motor designed for 60 cycles should never be operated on a 25-cycle line because of the excessive densities resulting in the magnetic circuit and the corresponding high hysteresis loss. The multiple frequency scheme for speed control never came into prominence owing probably to the complexity of the wiring and station apparatus.

*Varying the Number of Poles.* In another scheme for speed control the windings of the stator are connected through a series of switches; by proper operation of these switches it is possible to change the number of poles on the stator. Thus a motor might have its windings so connected through these switches that when they are thrown one way the motor has eight poles and when thrown in the opposite way the motor might have six poles. This scheme, while it gives an efficient speed control, requires rather complicated connections on the coils and so is not used as yet to a great extent.

*Cascade Connection.* In some installations (notably railway equipment) two motors are used connected in concatenation or cascade. The stator of the first motor is connected to the line, the slip rings of the first rotor are connected to the stator windings of the second, and the second rotor circuit is closed through a variable resistance. When all the resistance is cut out of rotor No. 2, both motors operate at half the speed they would have if directly connected to the line (with rotor short circuited). This

scheme is only applicable where two equal motors are connected to the same load, as in electric cars.

There are other methods for controlling the speed of an induction motor but they are all either inefficient or complicated and high in first cost. We must conclude as before that the induction motor is *essentially a constant speed motor.*

**99. Single-phase Induction Motor.** All of the previous analyses have been carried out with a polyphase motor in mind. In some respects the single-phase induction motor differs from the polyphase motor.

*Single-phase Motor has no Starting Torque.* Unless supplied with some additional starting device, such as a commutator, or extra stator winding with inductances or condensers, etc., *the single-phase induction motor has no starting torque.* But when the motor is operating near synchronous speed (with not more than about 20% slip) its characteristics are exactly like those of a polyphase induction motor. There are some slight differences, such as a lower power factor and less slip in the single-phase motor than in the polyphase, but these differences are slight.

The absence of starting torque is due to the fact that the stator has *only one set of coils* and is supplied with *single-phase current* only; *it can, therefore, produce only an oscillating magnetic field and not a rotating magnetic field.* To develop torque it is necessary to have a rotating magnetic field as was shown for the polyphase motor. When the motor is running at nearly synchronous speed the rotor currents, acting in conjunction with the single-phase stator winding, actually do produce a rotating magnetic field and for this reason the single-phase and polyphase motors act alike near synchronous speed.

*Split-phase Method for Starting a Single-phase Motor.* One way of designing a single-phase motor to give it a starting torque is known as the split-phase method. Although there is only one winding on the stator which can

carry much current, there is an additional winding at right angles to this, which is designed of sufficient size to carry a magnetizing current during the starting period only. After the rotor approaches synchronous speed this additional winding is automatically cut out of the circuit. Fig. 226 shows the connection for such a split-phase motor; the auxiliary coil is connected to the single-phase supply line *through a condenser*. This condenser, if large enough, will make the current in the auxiliary coil lead the current in the main coil by nearly 90°, hence the two coils act like the two coils of a two-phase motor and produce a rotating

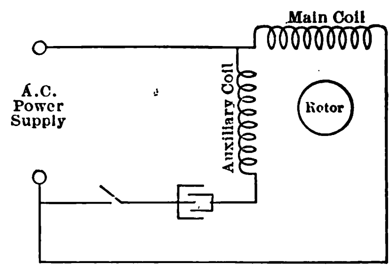


FIG. 226.—Connection for a Split-phase, Single-phase Induction Motor, using Condenser to Get the Out-of-phase Current in the Starting Coil.

magnetic field. After a suitable speed has been reached, the auxiliary circuit is opened to prevent overheating. An inductance may be used instead of a condenser to bring about the phase difference of the currents in the two windings.

*Commutator Type of Motor.* Another type of single-phase induction motor which is much used employs a rotor fitted with a commutator and brushes quite similar to a continuous-current motor. After the motor reaches the proper speed, all of the commutator bars are automatically short-circuited and the brushes lifted from the commutator. *This action* changes the rotor to an ordinary squirrel-cage

rotor. This motor starts on the same principle as the repulsion motor which is discussed in the next chapter. A view of the commutator end of the motor is shown in Fig. 227.

*Polyphase Motor Superior to Single-phase Motor.* It is evident that the polyphase motor is much more suitable for ordinary installations than the single-phase motor; in the first place the polyphase motor costs less per h.p.

FIG. 227.—View of a Single-phase Motor Using Commutator and Brushes for Starting. Wagner Electric Mfg. Co.

than the single phase and is more efficient in operation. In addition no extra devices are necessary with the polyphase motor to produce a starting torque. Because of these facts the single-phase motor is used only in small sizes, and where polyphase power is not available.

**100. Induction Motor Used as a Generator.** If an induction motor, connected to a polyphase line and running, is driven by some outside source of power at a speed greater

# CHAPTER XI

## COMMUTATING ALTERNATING CURRENT MOTORS

### SINGLE-PHASE SERIES MOTOR; REPULSION MOTOR; COMPENSATED REPULSION MOTOR

**101. Field for the Single-phase Series Motor.** As was explained in Chapter IV a motor suitable for electric traction must have a high starting torque, a variable speed-load curve and good efficiency when operating at widely differing speeds.

The *induction motor* runs at nearly constant speed irrespective of load and, if it is attempted to regulate the speed, either complex connections or decreased efficiency is necessary. The cascade connection of two motors and the scheme wherein the number of poles is varied both give only a *definite change in speed;* instead of having one speed of efficient operation the motor has two speeds, but neither of these schemes give a variable speed motor and in addition the switching and wiring become complicated. If rotor resistance is relied upon for speed variation a low efficiency is obtained at the same time.

The *synchronous motor* has a rather small starting torque (when started as an induction motor) and operates at constant speed, irrespective of load; it is evidently not suited for railway purposes.

*The single-phase series motor*, however, has starting and running characteristics very similar to those of the c-c. series motor and is thus suited for railway work. This *type of a-c.* motor has been developed as a railway motor

and is used to a limited extent for this purpose. The most notable example is the New York, New Haven & Hartford R.R. which has been operating for several years with single-phase series motor locomotives. It seems to be fairly successful in this installation but because of its inferiority to the c-c. series motor, it is not likely to come into extensive use.

**102. A-C. Series Motor vs. C-C. Series Motor.** At present, nearly all electric railways in this country use the continuous-current series motor as their motive power. The distribution of the electric power from the generating station to the car wheel is inefficient because of the many steps involved.

*Losses in a System Using C-C. Motors.* The power is generated as alternating-current, goes through step-up transformers at the station to the high-tension transmission line and so to the substation; there it goes through step-down transformers, to the synchronous converter where it is changed to c-c. power and is sent out through the c-c. feeders and trolley to the car. The speed control of the series motor requires the use of rheostats and considerable power is used up in these as well as in all the other parts of the system just enumerated; probably not more than 45%* of the power generated in the main station is delivered to the car wheel.

The system of distribution and probable losses in each part of the system are given in Fig. 229; the different percentages given show the approximate loss of power in that part of the system. These figures will vary widely for different installations.

*Losses in System Using A-C. Motors.* In case the alternating current series motor is used on the car the power distribution is much simpler. At the station there may be a step-up transformer connected directly to the

* Of course, this figure will vary widely in different installations, depending upon the type of apparatus installed, schedule of cars, etc.

trolley and feeders and then through an autotransformer on the car to the motor. Speed control is obtained by varying the ratio of the transformer so no rheostat losses occur at the motor; evidently the losses in such a distributing system will be much less than those of a c-c. system. If the a-c. motor were as efficient and reliable as the c-c. series motor probably all railway installations would use alternating-current power.

**103. Principle of Operation.** *A continuous-current series motor will run in the same direction which ever way it is connected to the c-c. line* provided *the relative connection*

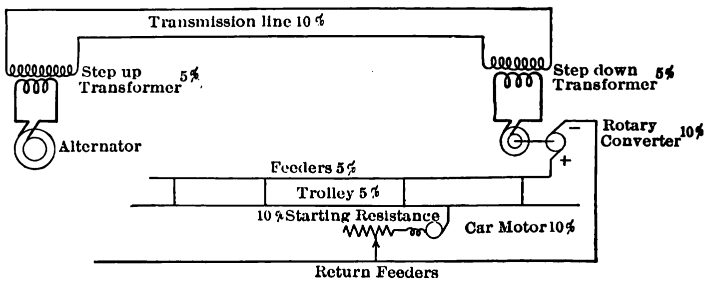


FIG. 229.—Possible Losses in the Various Parts of a c-c. Railway Distribution Syctem.

*of its armature and field is left undisturbed.* Hence, it follows that a c-c. series motor, connected to an a-c. line, would exert a *uni-directional torque,* and would revolve continuously in the same direction and not oscillate back and forth as might be expected.

*Difficulties in Running a C-C. Motor on an A-C. Line.* Such an application of the c-c. motor is not feasible because of the *low torque* which it would give, the *heating of the yoke and poles* and the *heavy sparking* which would occur at the brushes. The low torque would result from the high impedance of the field winding, which would permit but little current to flow through the motor; the heating

of the poles and yoke would result from the excessive hysteresis and eddy current losses due to the alternating magnetic field through this part of the magnetic circuit; and the sparking would result from certain causes taken up in a succeeding paragraph.

**104. Construction.** In a series c-c. motor the flux through the field frame is uni-directional and constant, and therefore this part of the magnetic circuit may be made solid, of cast steel. It is only the armature, in which the flux reverses, due to the rotation of the armature, which is necessarily made of laminated iron. But in the series a-c. motor the current through the field coils is alternating and hence the *flux through all of the magnetic circuit is alternating*, therefore, the entire field structure, as well as the armature core, must be made of laminated iron. Because of this fact the series a-c. motor cannot be constructed as cheaply nor of such rigid mechanical design as the c-c. motor.

*Windings.* The field coils of the a-c. series motor consist of but very few turns as compared to those of the c-c. motor and it is found that the field frame is best made without projecting poles, such as are used on the c-c. motor. The field frame resembles very much the stator of an induction motor, the field coils being imbedded in slots.

It would not be well to fill all the slots with field coils as such a design would not be efficient. But it is found necessary to put on the field frame an additional set of coils called the **compensating winding.** The two sets of coils (main field and compensating field) completely fill the slots of the field so that it resembles very closely the stator of an induction motor. The field of a series a-c. motor is shown in Fig. 230; this field is completely assembled and ready for the armature.

The armature of an a-c. motor resembles that of a c-c. motor very closely; the only difference is due to the manner

of winding. *The number of turns per coil* is very low in the a-c. motor and these coils are not connected directly to the commutator bars but through *resistance leads*, to be explained later.

**105. Power Factor—Compensating Winding.** If a c-c. series motor were operated on an a-c. circuit, the power factor would be very low, probably not more than .30 or .40. This low power factor would be due to the high

FIG. 230.—View of the Wound Field Structure of a Series Single-phase Railway Motor. Westinghouse Elec. and Mfg. Co.

inductance of the field and armature windings and could be increased only by decreasing the self-induction of these two windings.

*Compensating Winding.* We know that an a-c. system with a low power factor is very inefficient, both from the standpoint of first cost and of operating cost; the series a-c. motor must therefore be designed with low self- induction if it is to be successful. The self-induction of the field winding is kept low by using *fewer turns* than would be

used for a similar c-c. motor, and the self-induction of the armature winding is reduced to practically zero by the use of a *compensating winding.*

This winding consists of a set of coils, wound in slots in the field frame in such a manner that their magnetomotive force is just equal and opposite to that of the armature coils. Hence the armature cannot build up a magnetic field because of these compensating coils and so it has no self-induction. The compensating winding is connected in series with the armature so that the magnetic effects of the armature coils are neutralized at all loads.

*Low Frequency Power Necessary.* Even though the self-induction of the armature is reduced to zero by the compensating winding, the motor cannot be successfully used on 60-cycle circuits. The self-induction of the field coils is so large that the power factor of the motor is small if used on a circuit of greater frequency than 25 cycles. The advocates of this type of motor have agitated for 15-cycle power for railway operation, but this frequency is not likely to become standard in America. Practically all alternating-current series motors are designed for 25-cycle power.

*Low Flux Density.* The flux density in an a-c. motor must be kept low in order to prevent heavy hysteresis and eddy current losses in the field frame; thus for a given rating the a-c. motor is larger than the c-c. motor. Also, to produce the required torque, the armature must have a larger number of conductors in the a-c. motor because of the low flux density used; this larger number of armature turns does not increase the self-induction of the motor because of the action of the compensating winding.

In Fig. 231 is shown a cross-section of an a-c. series motor showing the relative positions of the main field, compensating field, and brushes. As the compensating coils carry twice as much current as the armature coils, it is necessary to have only half as many turns in the com-

pensating coils as in the armature. In Fig. 231 the compensating coils are indicated by dotted lines and the main field coils by full lines.

**106. Commutation.** Sparkless commutation is a very difficult thing to obtain on the a-c. series motor; of course, in the c-c. motor commutation is the most difficult problem for the designer to solve but in the a-c. motor it is a much harder problem.

The difficulties met in the c-c. motor are present in the a-c. motor and, in addition, *there is a transformer effect of*

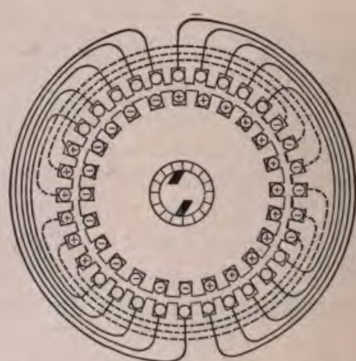

FIG. 231.—Sketch of the Winding of a Series Single-phase Motor, Showing Compensating Winding.

*the field on the armature coils which may produce a large current in those coils short circuited by the brushes.* In Fig. 232 is shown a diagram of the field and armature coils, a ring armature being shown for simplicity of representation.

*Short-circuited Coils have Transformer E.M.F.* The coils marked $X$ and $Y$ are short circuited by the brushes and these coils are threaded by the field flux, which is alternating. Hence an e.m.f. will be induced in coils $X$ and $Y$ just as though they were the secondary winding of a transformer of which the field coils represent the

primary. This *transformer e.m.f.* will set up a large current in the short-circuited coils and the rupturing of this current as the coil moves from under the brushes causes heavy sparking at the commutator.

*Commutating Poles of no Use on an A-C. Motor.* Commutating poles cannot be used to overcome the difficulty as in the c-c. motor because *this transformer e.m.f. in the short-circuited coil is greatest when the motor current is passing through its zero value.* Hence, if commutating poles were used in series with the armature as in the c-c. motor, the

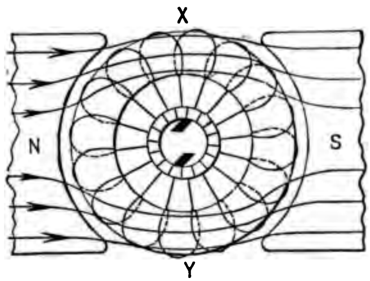


FIG. 232.—Sketch to Show Reason for High Current in a Coil During Commutation, due to "Transformer" e.m.f.

flux from the commutating poles *would be zero when it should be a maximum.* The method of eliminating the trouble is not by commutating poles but by increasing the resistance of the circuit through which the transformer current flows.

**107. Resistance Leads.** The resistance of the coil itself is not increased but an extra resistance is introduced in the leads connecting the coils to the commutator bars. These leads generally consist of a piece of resistance wire, which is placed in the bottom of the same armature slot in which the coil is to be placed. These leads have a resistance of about twice that of the coil itself and are

introduced into each commutator connection as shown by $r,r,r,$ in Fig. 233.

*The Resistance Leads do not Materially Increase the Armature Resistance.* The path for the transformer current is made up of the coil, two resistance leads, two commutator bars and the brush, so that the use of these leads cuts down the transformer current in a coil to about one-fifth the value it would have without them.

The addition of these resistance leads does not materially affect the resistance of the armature as a whole because the total armature resistance between brushes is

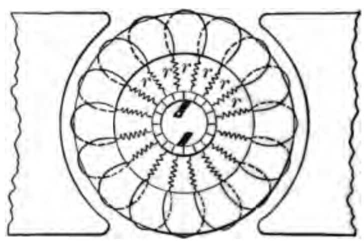


FIG. 233.—To Show where Resistance Leads are Used.

many times that of one coil and the load current has to flow through only two of the resistance leads in addition to the coils. Thus if the armature had 100 coils and each resistance lead (sometimes called *preventive lead*) had twice the resistance of a coil, the resistance of the armature between brushes would be 54/50 as great as though no resistance leads were used, while the resistance of the path of the transformer current would be increased five times. It is claimed that the use of such leads makes sparkless commutation possible at all loads on the a-c. series motor and also that the leads show no deterioration after much service.

**108. Operating Characteristics.** The operating, or *running,* characteristics of the motor resemble very much those

of the c-c. series motor. A small series motor tested in the laboratory gave results as shown in Fig. 234.

The torque, or tractive effort, increases nearly as the square of the current, being a maximum for the lowest

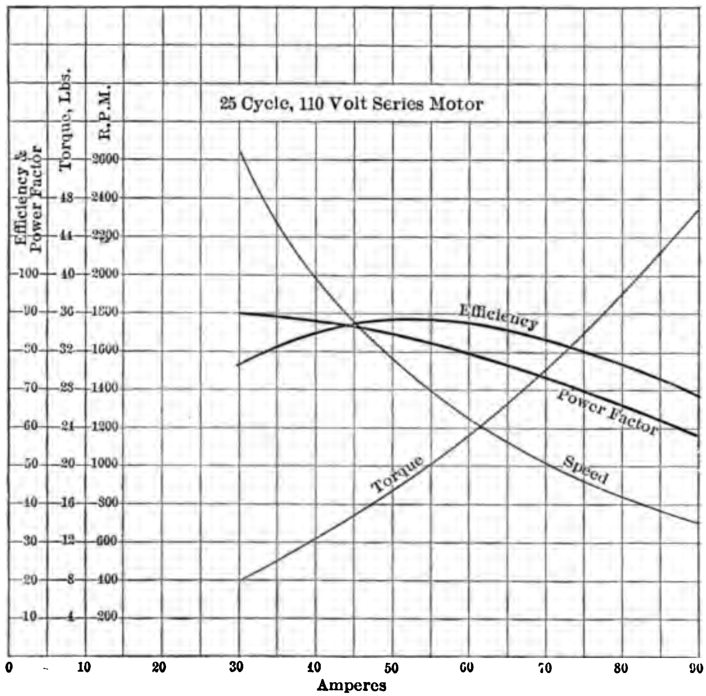


FIG. 234.—Operating Characteristics of a Small Series Single-phase Motor.

speeds; this is one of the characteristics that make the motor suitable for tractive work. The efficiency is fairly high for all loads in the working range of the motor, but is lower for all loads than that of a corresponding c-c. motor. The extra iron and copper loss in the a-c. motor account for this fact.

The power factor is a maximum for the high speeds and gradually decreases with increase of load. The reason for this may be seen by reference to the vector diagram shown in Fig. 235. The impressed voltage on the motor is constant and in Fig. 235 is given by the radius $OD$ of the circular arc $CC'D$. The phase of the current is assumed as $OI$. There are three reactions balancing the impressed e.m.f. of the motor, viz., the inductance reaction, which is proportional to the current, the resistance reaction, also proportional to the current, and the c.e.m.f. due to the rotation of the armature conductors.

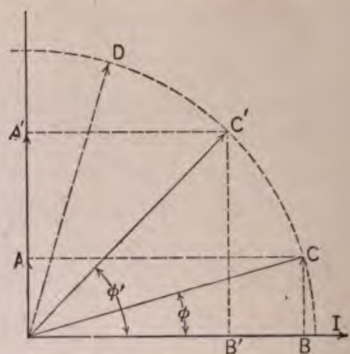


FIG. 235.—Vector Diagram of the Series Single-phase Motor.

For a current of 10 amperes the inductance drop of the motor tested was $OA$ and the power factor was cos $\phi$. For 40 amperes the inductance drop was $OA'$ and the power factor was cos $\phi'$, which is eveidently less than cos $\phi$.

**109. The Repulsion Motor.** This motor is one employing a wound armature with commutator and brushes, but the armature circuit is not connected electrically to the power supply line. It was first developed by Elihu Thomas in 1887, but has not yet come into very extensive use. It has operating characteristics very similar *to those of* the series a-c. motor. It has an advantage

over the series motor in that its armature is not connected to the power line and so its power supply, which is fed into the field circuit only, may be of much higher voltage than can well be used on the series motor.

*Principle of Operation.* The principle on which the motor operates may be understood by reference to Fig. 236. The field circuit is connected to the power supply and so an alternating flux is set up in the armature. The armature brushes are short circuited and the plane of the brushes, $A-B$, is at an angle with the direction of the magnetic field. An e.m.f. is induced in the armature coils by the alternating field flux, and this e.m.f. causes a current to circulate through the armature coils and the path con-

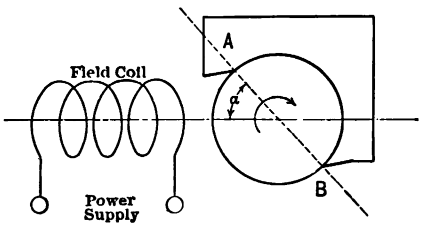


FIG. 236.—Circuits of a Simple Repulsion Motor.

necting the brushes together. The armature conductors carrying current react on the magnetic field set up by the field coil and so produce a torque. The magnitude of this torque depends upon the value of the angle $\alpha$, Fig. 236, and the direction of the torque is always in the same direction as that in which the brushes $A-B$ have been moved away from the center line of the field.

*Torque Varies with the Position of the Brushes.* The dependence of the torque upon the angle $\alpha$ may be seen by reference to Fig. 237. *Any armature having short-circuited brushes may be represented by one short-circuited turn, this turn being in a plane 90° away from the plane of the brushes.* In Fig. 237, for example, the short-circuited

coil, $AB$, is equivalent to an armature having its brushes in the plane $XY$, parallel to the field. Now such a short-circuited turn as $AB$ (Fig. 237) would have a large short-circuit current flowing in it as soon as the field of the motor was excited, but this large current could produce no turning effort because the conductors $A$ and $B$, in which the current is supposed to be circulating, lie in a zero magnetic field.

Suppose, now, that the short-circuited brushes of the repulsion motor are advanced 90° so that the one armature

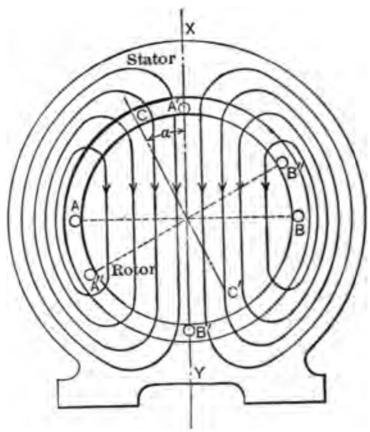


FIG. 237.—To Show how Torque Depends upon Brush Position.

coil, representing all the armature winding, is in the position $A'B'$, Fig. 237. Evidently the coil could produce no turning effort because no current would circulate in it. The plane of the coil is parallel to that of the flux and hence there is no e.m.f. induced in it by the alternating field flux.

If, now, the brushes are placed in such a position that the equivalent armature coil is shown by $A''B''$ in Fig. 237, it is evident that there will be a current flowing in the conductors of the short-circuited armature and that these

conductors lie in a magnetic field. Hence there will be a force exerted between the field and the armature conductors tending to make the armature turn. This torque will continue to be in the same direction as the flux alternates, because *the current in the armature and the field flux both change together*, so that the force between them is constantly in the same direction.

To discuss this point more completely it would be necessary to consider the relative phases of the field flux and armature current and this would complicate the question too much. We have given enough analysis to show

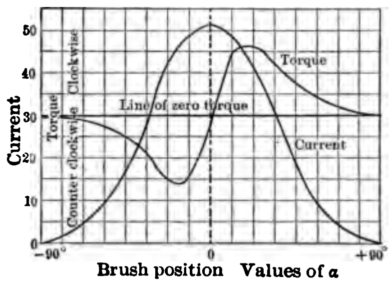


FIG. 238.—Torque and Current of the Repulsion Motor Vary Greatly with the Position of the Brushes, as Shown Here.

that the torque of such a motor (like that of the series a-c. motor) is uni-directional and pulsating.

*Direction of Rotation.* When the armature conductors are represented by the equivalent coil $A''B''$ the brushes must be at right angles to the plane of this soil, as shown by $CC'$ in Fig. 237. When the brushes are placed back of the center line of the magnetic field, the armature will rotate in a counter-clockwise direction and vice versa. Hence to vary the torque of a repulsion motor in magnitude and direction it is only necessary to change the position of the brushes on the commutator. The variation of the tcrque and current with the position of the brushes is

shown in the curves of Fig. 238. It is seen that the current, as well as the torque, varies greatly with the position of the brushes.

**110. Compensated Repulsion Motor.** The power factor of the repulsion motor described in the last paragraph is rather low and this is, of course, objectionable. Several schemes have been developed for increasing the power factor; a motor in which this is attempted is called a **compensated repulsion motor.**

The general scheme is to have a winding so placed on either the field or armature that the field inductance is

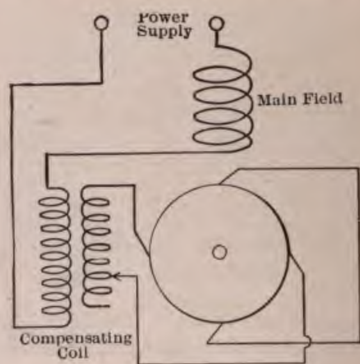


FIG. 239.—One Method of Compensating a Repulsion Motor

practically neutralized. One of the simplest of these schemes is shown in Fig. 239. This type of motor was developed by Winter and Eichberg; it gives the same characteristics as the ordinary repulsion motor with the exception that the power factor is much higher. The short-circuited brushes are placed in the plane of the magnetic field and an extra set of brushes, at right angles to the first pair, are connected to the secondary of a transformer, the primary of which is placed in the power supply line, in series with the motor field winding. The secondary has several taps so that the power factor may be maintained high at various speeds.

# CHAPTER XII

## RECTIFYING DEVICES

### THE SYNCHRONOUS CONVERTER; MERCURY ARC RECTIFIER; VIBRATING RECTIFIER

**111. Need of Rectifying Devices.** We have mentioned before the fact that it is generally best to generate electrical power in the form of alternating-current power because of the ease with which the voltage may be " stepped up " for transmission and then " stepped down " again for use in motors, lamps, etc. There are many installations in which the power is desired as continuous-current power at the place where it is used; it must generally be transmitted from the main generating station as high voltage a-c. power and then changed into c-c. power at the place where it is used. This is the function of a rectifying device —to change a-c. power into c-c. power or vice versa. Charging storage batteries from a-c. lines and running c-c. railway systems from a-c. power lines are the two cases where rectifiers are mostly used to-day. For the latter purpose **synchronous converters** (also called **rotary converters**) are always used, while the **mercury arc** and **vibrating rectifiers** are used for charging storage batteries from a-c. lines.

**112. Principle of Operation of the Synchronous Converter.** The synchronous converter is really a combined synchronous motor and continuous-current generator; it receives alternating-current power as a synchronous motor running at synchronous speed and delivers continuous-current power. In appearance and construction it is prac-

tically identical with a c-c. generator with this addition; on that end of the armature opposite to the commutator is mounted a set of slip rings (the number of rings depending upon the number of phases desired) which are connected by taps to the armature winding just as though this winding had been intended for use as a synchronous motor.

In Fig. 240 is shown a small, three-phase synchronous

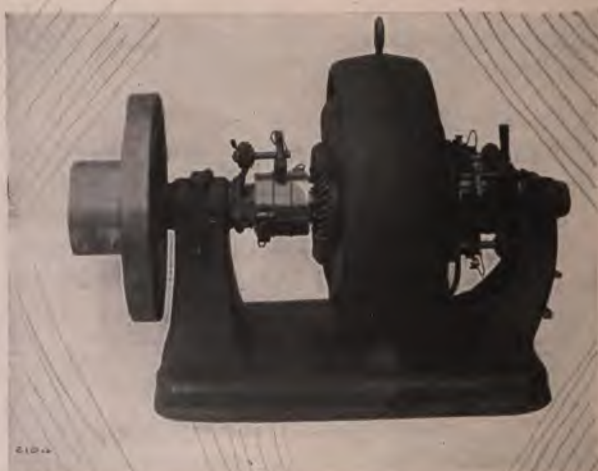

FIG 240.—General View of a Small Three-phase Synchronous Converter, Showing Commutator on One End of the Armature and Slip Rings on the Other. Fort Wayne Electric Works.

converter; it is seen to be identical in appearance with a c-c. generator, with, however, the slip rings added on one end of the armature.

Suppose that such a machine is running, as a synchronous motor; the action of the commutator and revolving armature winding will be just the same as though the armature was being driven by a belt and pulley instead of by the synchronous motor action and hence there will

be, on the brushes, a uni-directional e.m.f. If a load circuit is connected to the brushes, c-c. power will be supplied to this load. As the amount of c-c. power output increases, the a-c. power input will correspondingly increase—in fact, the input on the a-c. end must always equal the c-c. output plus the losses in the machine. The speed remains constant (at synchronous speed for the machine considered as a synchronous motor) irrespective of the load.

*Continuous Voltage Independent of Load.* The value of the continuous voltage is nearly independent of the load *provided the alternating voltage is maintained constant;* this point is covered more completely by saying that, for any converter, the ratio of the alternating voltage to the continuous voltage is a constant. Moreover, this ratio is independent of the field current, the frequency of the a-c. supply, and the size of the machine; it depends only on the number of phases for which the winding is tapped on the a-c. end.

A three-phase converter has one ratio and a single-phase converter has another, but the ratio for all three-phase converters is the same, independent of size or frequency. The value of this ratio for different phases will now be derived.

**113. Voltage Ratio and Its Dependence upon the Number of Phases.** Suppose a converter winding consists of only twelve coils in a bipolar field, as shown in Fig. 241, and that each coil has the same number of turns and each is spaced from its neighbor by $\frac{1}{12}\times 360° = 30°$. The derivation of the voltage ratio depends upon the assumption that *each coil generates a sine wave e.m.f.* and hence, that the e.m.f. of each coil may be represented by a rotating vector.

*Vector Diagram for the E.M.Fs. of Different Coils.* The vector diagram for the e.m.f. generated by each coil is given in Fig. 242; all the vectors are of the same length and each is spaced from its neighbor by 30°. Now we know that

alternating e.m.fs. must be added vectorially (instead of arithmetically) to give the resultant e.m.f., hence, if we tap the winding of Fig. 241 at $A$ and $B$ (diametrical points), the vector giving the voltage $A$–$B$ will be found by adding *vectorially* the e.m.fs. of coils 1 to 6 inclusive. But this vector will evidently be the diameter of a regular polygon having for its sides the vectors given in Fig. 242.

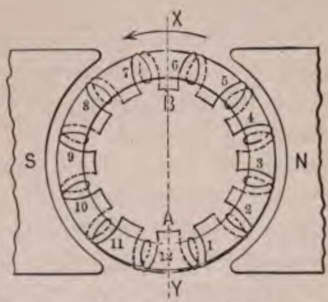


FIG. 241.—Elementary Winding for a Synchronous Converter, Single-phase Taps at $A$ and $B$.

*Voltage for Single-phase Taps.* This polygon is shown in Fig. 243 and the voltage between the points $A$ and $B$, Fig. 241, is shown by the line $AB$ in Fig. 243. The c-c. brushes, by means of the commutator, are continually maintained at a difference of potential equal to $AB$, Fig. 243, because the brushes continually make contact with the winding on the line $XY$, and so there are continually six coils adding their e.m.f. between the c-c. brushes.

But suppose that the points $A$ and $B$ are connected to a pair of slip rings; the maximum e.m.f. between the rings will be $AB$, Fig. 243, and this is the same as the e.m.f. between the c-c. brushes.

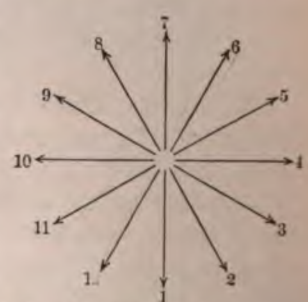

FIG. 242.—Vector Diagram of the e.m.f's. Generated in the Different Coils of Fig. 241.

Hence we have the relation that, on a single-phase converter, the *maximum alternating voltage is the same as the continuous voltage*, and hence *the virtual alternating*

*voltage of a single-phase converter is equal to the continuous voltage* $\times \frac{1}{\sqrt{2}}$. This ratio is independent of the size of the machine, the speed, the number of poles, or anything else; for a single-phase converter this is a fixed quantity, it cannot be varied.

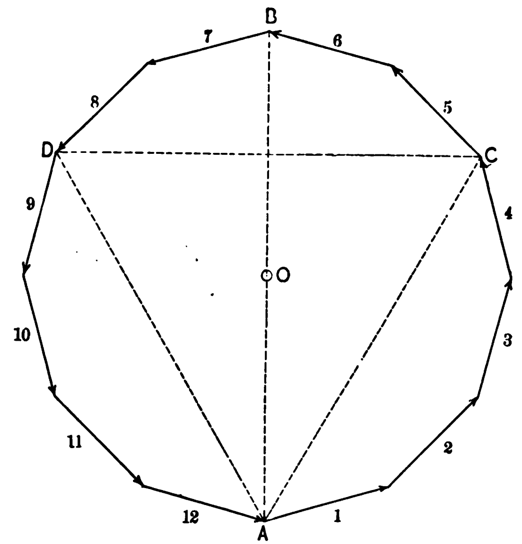


FIG. 243.—The e.m.fs. of the Coils of the Closed Circuit Winding Must Form a Closed Polygon.

*Voltage for Three-phase Taps.* Now, suppose the winding shown in Fig. 241 is to be tapped for a three-phase a-c. supply; the taps would be at *A*, *C*, and *D*, Fig. 243. Between each of these taps, there are four coils and the vectors giving the different e.m.fs. are shown in Fig. 243 by *AC*, *CD*, and *DA*. These vectors are equal to each other and are 120° apart, as they should be for a three-phase winding.

The length of the vector $AC$ can be found in terms of the vector $AB$ in the following manner. In Fig. 244 the construction of Fig. 243 is duplicated to some extent, but instead of the vector polygon we have the circumscribing circle. The angle $\alpha$, Fig. 244, is equal to 120° for the

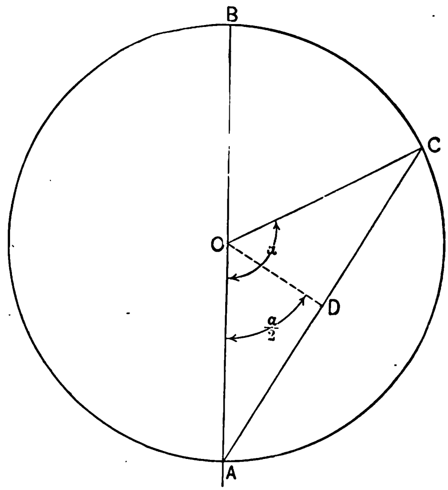


FIG. 244.—Diagram for derivation of Formula Giving the Ratio of a Synchronous Converter.

three-phase taps $AC$, hence $COD$ $(=\alpha/2)$ is equal to 60°. Therefore, we have

$$AC=2AD=2(OA \sin \alpha/2)=AB \sin \alpha/2=AB \sin 60°.$$

But $\quad AB=$ the continuous voltage $\div \sqrt{2}$.

Hence

$AC$ (three-phase voltage)

$$=\frac{\text{the continuous voltage}}{\sqrt{2}}\times \sin 60° \quad . \quad (77)$$

$$=\text{the continuous-voltage}\times .612.$$

Therefore, the alternating voltage of a synchronous converter is equal to 61.2 % of the continuous voltage and this ratio is independent of the size of the converter, etc.

The voltage ratio for any other number of taps can be found by substituting the proper angle for $\alpha/2$.

The actual ratio of voltages on a synchronous converter are somewhat different from those obtained from this theoretically derived formula. There is an impedance drop in the armature, which, of course, varies with the load and this makes the ratio vary slightly as the machine is loaded. A three-phase converter having a ratio of .615 at no load might have a ratio of perhaps .63 or more when carrying full load. If the wave of alternating e.m.f. impressed is not a true sine curve of course the ratio will be different from that obtained on the assumption of sine curve of e.m.f.

**114. Current Forms in the Coils of a Synchronous Converter.** The rated capacity of a synchronous converter is generally fixed by the safe rise in temperature, the same as for any other electrical machine. Of course, the heating increases with increase of load due to the increased $I^2R$ loss in the armature coils.

Now the currents flowing in the different coils of a synchronous converter armature are of very peculiar shape. An alternating current is flowing into the armature at the a-c. taps and a continuous current is flowing away from the c-c. brushes. The actual current in any coil is the difference of these two currents.

*Current Due to the C-C. Load.* Consider the armature shown in Fig. 241, connected to a commutator and supplying a c-c. load, i.e., acting merely as a c-c. generator. The currents in the different coils would be rectangular waves, as shown in Fig. 245. If the load current were 10 amperes, the current in each coil would be 5 amperes because the armature has two paths.

As each coil moves under a brush its current is changed

from one direction to the opposite direction, but while the coil is moving from one brush to the other its current is constant in magnitude and direction. Each coil would have its current commutated, or changed in direction, 30° (one-twelfth of 360°) later than its neighbor and so the current forms of Fig. 245 are seen to be correct.

*Current Due to A-C. Input.* Now consider the current in each coil, supposing the machine running as a single-

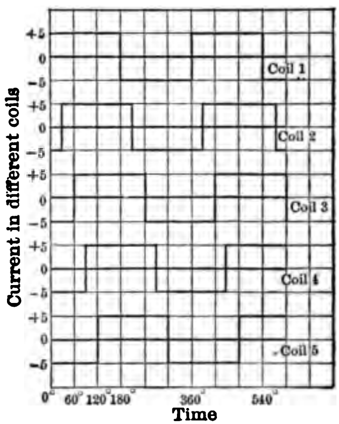


FIG. 245.—Currents in the Different Coils Due to c-c. Load.

phase synchronous motor. The current in each coil will be a sine wave (supposing a sine wave of e.m.f. to be impressed) and the maximum value of the current in any one coil is equal to one-half the maximum of the current in the single-phase line supplying the power; this is true because there are two paths in the armature between which the line current divides equally.

*Ratio of Alternating Current to Continuous Current in a Single-phase Converter.* Neglecting the losses in the machine,

to make the equation simple, we may now write for the single-phase converter,

$$\text{a-c. input} = \text{c-c. output}$$

But $$E_{\text{alt.}} = .707E_{\text{con.}}$$

Hence, $$I_{\text{alt.}} = 1.41I_{\text{con.}},$$

which gives the relative values of the continuous current and the virtual alternating current. We know that the maximum value of an alternating current is equal to $1.41\times$the virtual value, so that

$$I_{\text{alt.}}(\text{maximum}) = 1.41I_{\text{alt.}}(\text{virtual}) = 2\times I_{\text{con.}}$$

Therefore, if the machine running as a single-phase synchronous converter is supplying 10 amperes to the c-c. line ( 5 amperes in the individual coils, as shown in Fig. 245), the *maximum* value of the current in the a-c. supply line is 20 amperes and the maximum value of the alternating current in a coil is half of this value, or 10 amperes.

*Actual Current in a Coil.* The actual current in any coil of the converter is the resultant of a sine wave of current (maximum value equal to 10 amperes) and the rectangular current shown in Fig. 245. Fig. 246 shows the result of subtracting the continuous current in a coil from the alternating current, on the supposition that the alternating current has its maximum value when coil 1 is undergoing commutation.

*Peculiar Current Forms.* From Fig. 246 it is seen that the currents in the individual coils are very different in magnitude and form; this makes the heating of the various coils different, it being much greater in those coils near the a-c. taps. In case the converter is operating with a power

factor different than cos $\phi=1$, that coil having the greatest current will be close to the a-c. tap but on one side of the tap only; the adjacent coil, connected on the other side of the a-c. tap will be much cooler.

**115. Heating of Coils.** The heating of the different coils will evidently be different because the heating depends upon the magnitude of the current; it follows that some

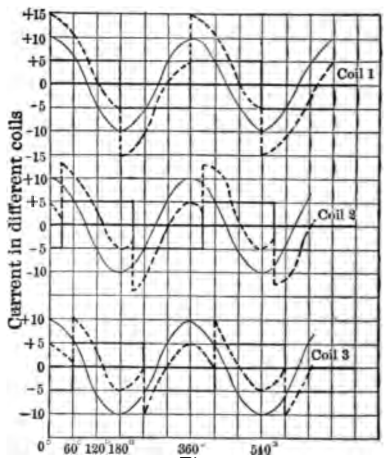


FIG. 246.—Actual Current in any One Coil Must be the Resultant of the Rectangular Curves of Current Output and the Sine Wave of Current Input.

coils will be hot when the converter is operating and others will be comparatively cool. *In those coils which run coolest the alternating current flowing into the coil and the continuous current flowing out of the coil nearly neutralize each other;* the more completely this neutralization takes place the cooler the coil will be.

*Neutralization of Currents in Various Coils.* In a polyphase synchronous converter, this neutralization of currents

is much more complete than in a single-phase converter, also the heating of the different coils becomes more nearly alike as the number of phases is increased. It is possible to develop an expression for the heating in the various coils for different numbers of phases;* such an analysis yields results as shown in Fig. 247.

The base line of this set of curves represents the distance between consecutive taps; it would correspond to half the

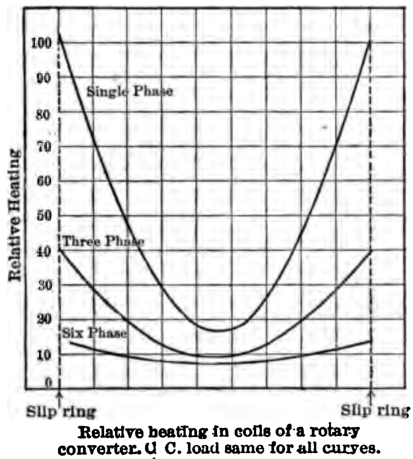


FIG. 247.—Comparative Heating in the Coils between Adjacent Taps of a Synchronous Converter.

circumference for a single-phase, bi-polar converter, one third for a three-phase, one-sixth for a six-phase, etc. The ordinates represent the relative heating in the different coils for a given c-c. output of the converter. It is seen how the heating of the coils decreases and becomes more nearly alike in the different coils as the number of phases is increased.

* Alternating Currents, Hay, p. 241 et seq.

*Heating of Coils when the Power Factor is not Unity.* Fig. 247 shows the conditions for a converter having normal excitation, that is, with the power factor of the machine unity. If the excitation is changed so that the converter is operating at a power factor less than unity (due either to a lagging or a leading current) the relative heating in the different coils is yet more varied; there is not only more difference between the hottest and the coolest coil than when the machine has normal excitation, but, in addition,

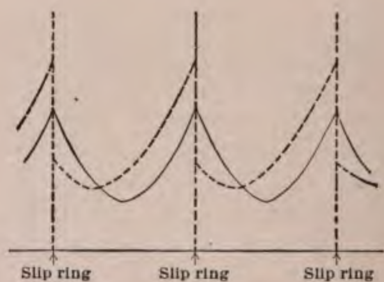


FIG. 248.—Relative Heating a Different Power Factor; the Full Line is for cos $\phi=1$ and the Dotted Line for a Lagging Current in the Converter Armature.

nearly all coils are hotter. This is shown in Fig. 248, where the full-line curve shows the relative heating in the different coils for cos $\phi=1$ and the dotted curve shows the same results when the converter is run with an underexcited field.

**116. Capacity of a Synchronous Converter.** It is seen from Fig. 247 how the heating of the coils is diminished as the number of phases is increased and hence it is evident that a *given armature* will have *more capacity as a six-phase converter than as a three-phase, or greater as a three-phase than as a single-phase, etc.* If we have a certain armature which has a safe capacity of 100 kw. used as a continuous-

current machine it will have more or less capacity used as a synchronous converter, depending on the number of phases, as given below.

| | | | | | |
|---|---|---|---|---|---|
| Number of phases | 1 | 3 | 4 | 6 | 12 |
| Safe capacity in kw | 85.2 | 133 | 162 | 193 | 219.5 |

If the number of a-c. taps were increased to a very great number, the safe capacity of the armature would increase to 230 kw.

*Converters always Polyphase.* Single-phase converters are practically never used because they have such a low capacity and in addition they have a marked tendency to "hunt," as explained in the chapter on synchronous motors. Most converters are operated three-phase, although in the larger sizes the tendency is to wind them six-phase because of the increased capacity obtained. They are practically never used twelve-phase because the increase in capacity is obtained only at the expense of complication and increased cost of the brush rigging, rings, etc.

**117. Methods of Starting Synchronous Converters.** The synchronous converter is essentially a synchronous motor when considered from the input side; some method therefore must be used for starting and synchronizing it with the line. There are three different methods in use to-day; starting as a c-c. motor from the commutator end; as an induction motor from the slip-ring end; or by having some auxiliary starter, such as a small induction motor.

*Starting from the Continuous Current End.* In order to start a converter from the c-c. end it is necessary to have a c-c. supply available of the same voltage as that which the converter gives when in normal operation. If for example, the converter is only one of several in a sub-station and one or more are in operation, the c-c. power for starting may be taken from the c-c. end of those already operating. A starting rheostat is put in the armature circuit and gradually cut out as the machine (starting

as a shunt wound c-c. motor) speeds up; the speed is adjusted by the field rheostat to bring the converter into synchronism with the line and then the converter is switched to the line after the indicating device (lamps or synchronoscope) shows the proper phase.

*Starting as an Induction Motor.* The induction motor method of starting is becoming more and more common. Half-voltage taps are supplied on the transformers which normally supply the converter, and with the field circuit of the machine open, the a-c. end of the converter is switched to the half-voltage line. When it has accelerated to nearly synchronous speed, the starting switch (which is double throw) is thrown over to the normal voltage line and then the field circuit is closed (connected to the c-c. end of the converter), and the field current gradually increased to its normal value.

*Field "break-up" Switch.* In using this method of starting a very high voltage may be induced in the field coils, due to the field coils acting like the secondary of a transformer, the armature being the primary; the field circuit must be subdivided to avoid puncturing the insulation of the field coils. This is done by a field "break-up switch" generally mounted on the frame of the machine.

Fig. 249 shows a 2000-kw. synchronous converter on the frame of which may be seen the field "break-up" switch; on this machine a seven-pole switch is used to break the field circuit in several places. The large single-pole switch on the field frame is connected in the equalizer bus-bar circuit.

*Reversed Polarity.* The field current may start to build up in the wrong direction, making the c-c. instruments connected in the converter circuit deflect backward; to remedy this difficulty it is necessary to make the converter slip back one pole before putting on the field excitation.

*Sparking at the C-C. Brushes.* If a converter is equipped 'th commutating poles, this method of starting is likely

to cause bad sparking at the c.-c brushes while the machine is speeding up. To prevent this, the brush holders are equipped with a simple lever arrangement whereby the brushes may easily be lifted off the commutator, while the armature is accelerating, and then dropped back in place on the commutator when synchronous speed has been reached and the danger of serious sparking is over.

*Use of Auxiliary Starter.* When the third method of starting is used, a small induction motor is mounted on one of the armature pedestals, its rotor being mounted directly on the shaft of the converter. The stator is wound for the same voltage and number of phases as the converter armature and the motor has just sufficient capacity to run the converter at synchronous speed when it is supplying no load. The induction motor always has one pair of poles less than the converter (why?) and has a capacity rating of from 5 to 10% of that of the converter.

*Large Commutator Required on a Polyphase Converter.* A cut of a large six-phase converter is given in Fig. 249. It is to be noticed that on this converter the commutator is much larger than it would be on a c-c. generator of the same size. This is because of the fact brought out in the last paragraph; the capacity of the six-phase converter is practically twice as much as that of a c-c. generator of the same size (*size—not capacity*) and hence the c-c. brush rigging and the commutator must be of twice the current capacity as that required for a c-c. generator of the same size.

**118. Compounding a Synchronous Converter by Series Field and Line Inductance.** We have proved that the ratio of continuous voltage to alternating voltage is fixed for a given synchronous converter. It is not therefore, at once evident how a converter may be designed to give a voltage on the c-c. end, increasing with load; yet this is generally desired. For use in railway and lighting installations a converter is generally desired with about 10% compounding; for example, the specifications for a rail-

way converter might call for 550 volts at no load, 600 volts at full load, and those for a converter for a lamp load 225 volts at no load, 250 volts at full load.

*Necessary Increase in Impressed Voltage.* But the ratio of the continuous voltage to the alternating voltage is fixed and it is therefore evident that if it is desired that the

FIG. 249.—A Six-phase Synchronous Converter, Showing the Field "break-up" Switch Mounted on the Frame. Westinghouse Electric & Mfg. Co.

continuous voltage should increase with the load *it can be accomplished only by causing the impressed alternating voltage to increase correspondingly with load.* A railway converter to give 550–600 volts would require an impressed alternating voltage of $550 \times .612 = 337$ volts, at no load,

and an alternating voltage of $600 \times .612 = 367$ volts at full load. However, slightly more than this voltage would be required to overcome the effect of armature impedance drop which increases with the load.

The ordinary method for compounding a converter is to have an *inductance inserted in the a-c. line supplying the converter* and to equip the converter field with *a series winding* as well as a shunt winding. By use of this series winding, the excitation of the machine is increased with an increase of load and this increased excitation causes an automatic increase in the a-c. voltage impressed on the machine.

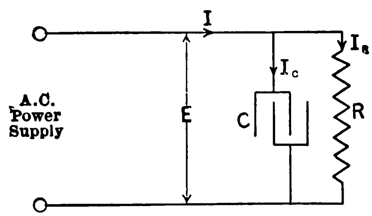


FIG. 250.—Circuit Electrically Equivalent to the Converter Armature.

*A Converter Similar to a Synchronous Motor.* Now in so far as its effect on the a-c. supply line is concerned, the synchronous converter acts exactly like a synchronous motor and hence, if it is overexcited, it draws from the line a *leading reactive current,* besides whatever active current it may be using. The magnitude of the reactive current depends upon how much the machine is overexcited; the more the overexcitation the greater is the leading current.

*Equivalent Circuits.* The armature circuit of the converter may be represented by a condenser and resistance in parallel as shown in Fig. 250. The current $I_r$, through $R$, represents the active current that the converter requires and the current $I_c$ flowing into the condenser represents

the reactive component of the converter current. As the overexcitation of the machine is increased, the capacity of the condenser $C$ must be imagined to increase proportionately in order that the circuit of Fig. 251 may correctly represent the conditions in the actual synchronous converter circuit.

In Fig. 251 the converter is again imagined as consisting of a resistance and a condenser in parallel, and there is an inductance $L$ in the supply line. The voltage of the line is constant (with a value equal to $E$, irrespective of the load and the excitation of the converter) and we wish to find the effect on $E_R$, the voltage impressed on the converter, as the

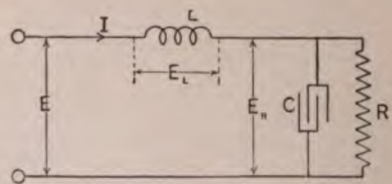


FIG. 251.—Inductance in the Supply Line Makes Compounding Possible, because of the Condenser Action of the Converter Armature.

excitation of the machine is increased. In Fig. 251 this increase of excitation is to be represented by an increase in the capacity of $C$.

*Vector Diagram of the Circuit.* The vector diagram of the current and e.m.fs. is shown in Fig. 252. Suppose that at first there is no superexcitation on the machine so that the current and voltage $E_R$ are in phase. A circular arc is constructed with $E$ as a radius; the e.m.f. to overcome the drop in the inductance $L$ is shown at $E_L$ and hence the voltage across the armature of the converter is found by vectorially subtracting $E_L$ from $E$. The result, $E_R$, is found to be slightly less than $E$.

If, now, some superexcitation is put on the converter,

giving a condenser current $I_c'$, the line current is found at $I'$; the e.m.f. to overcome the inductance drop is proportional to this current and 90° ahead of it and is shown at $E_L'$. By subtracting this $E_L'$ from $E$ we find the converter voltage at $E_R'$, which gives a voltage somewhat greater than the line voltage $E$. (It is to be noticed that in constructing this diagram $E_L$ and $E$ must always so combine that $E_R$ is found in phase with $I_R$; $I_R$ and the converter voltage $E_R$ must be in the same phase and on the vector diagram this is shown to be possible by the phase shifting of $E$.)

For still further increases in the field excitation of the converter the currents are shown by $I''$ and $I'''$ and the

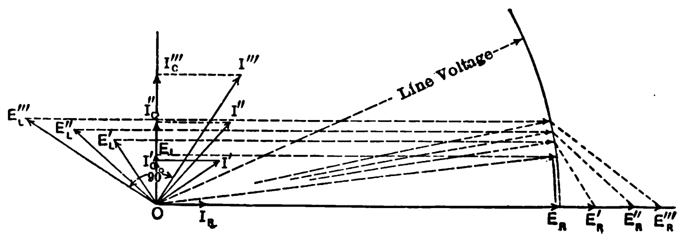


FIG. 252.—Vector Diagram of Compounding Action.

corresponding voltages are shown by $E_R''$ and $E_R'''$. It is thus seen that, when there is inductance drop in the line supplying the a-c. power to the machine, *it is possible to bring about an increase in the voltage impressed on the converter by sufficiently overexciting the field, even though the line voltage E, remains constant.*

*Compounding Accomplished Automatically.* The ratio of the alternating voltage to the continuous voltage is practically constant so that this increase brought about in the impressed voltage means a corresponding increase in the continuous voltage of the converter. The over-excitation of the converter field is automatically increased as the load increases by means of a *series field winding* in

addition to the shunt field; the shunt field has enough m.m.f. to give the machine normal excitation and the overexcitation of the converter is brought about entirely by the series field. By introducing sufficient series field it is possible to compound the converter to any degree desired. There is, however, a practical limit on the amount of compounding possible, for if too much inductance is introduced the converter is likely to hunt badly.

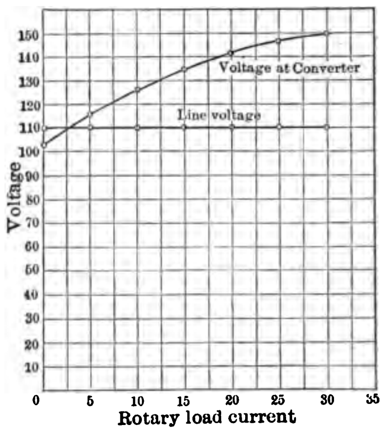


FIG. 253.—Curves Showing Compounding Action of an Overexcited Converter.

This method of compounding is accompanied by undue heating in some of the coils, as shown in Fig. 248.

*Example of Compounding.* Fig. 253 represents the effect of operating a small converter, having a strong series field, on a line having a correspondingly high inductance. These results were obtained in the laboratory; such heavy compounding is generally not found in practice.

**119. Compounding by the Synchronous Booster.** When this method of compounding is to be used, the armature of a small stationary field alternator is built up on the

same shaft with the armature of the synchronous converter. The field frame for the alternator is mounted on the side of the converter field frame.

*Construction of the Machine.* The alternator armature winding must be of the same number of phases as the converter armature winding; its current capacity must be equal to that of the converter armature; and its normal generated voltage must be equal to the desired amount of compounding. The different phases of the armature winding are kept separate. The beginning of each phase is connected to a slip ring and the end is connected to one tap of the converter armature.

The a-c. line supplying power to the converter is connected (through brushes) to the alternator slip rings. Hence the converter is connected to the a-c. line through the armature of the alternator, which, by suitable excitation of its field, may be made either to raise or lower the voltage impressed on the a-c. taps of the converter. By suitably winding the alternator field coils, and connecting them in series with the continuous-current load, the compounding may be made automatic.

A synchronous converter fitted with a synchronous booster is shown in Fig. 254. This machine was built for 10% compounding, therefore, the booster is somewhat more than 10% of the capacity of the converter itself.

**120. Auxiliary Pole Synchronous Converter.** It has been stated that the ratio of voltages was fixed for a certain converter and that this ratio was independent of the field excitation, etc. But it has recently been shown that if the field pole of a converter is made up in two or more parts, the excitation of each part being under separate control, a certain amount of variation of the ratio si possible. A machine having its field poles so constructed is called an **auxiliary pole, or split-pole converter**; it has been developed by one of the large manufacturers but has not yet come into very general use.

A discussion of the theory of this type of converter is beyond the scope of this text; operating curves of a small three-phase auxiliary pole converter are given, however, in Fig. 255. In this machine it was possible to compound the continuous voltage from 92 volts to 135 volts. As the excitation of the auxiliary pole was varied from negative

FIG. 254.—A Synchronous Converter Fitted with a Synchronous Booster. Westinghouse Electric and Mfg. Co.

to positive, some variation in the strength of the main field poles was required in order to maintain the power factor of the machine high.

**121. Motor-generator Sets.** One disadvantage of using a synchronous converter to obtain c-c. power from an a-c. supply is that the continuous voltage is fixed; in many cases (*notably* in mine installations) c-c. power of variable voltage

is required. For this purpose a motor-generator set is used instead of a synchronous converter. An induction, or synchronous, motor takes power from the a-c. line and drives a continuous-current generator, the field excitation of which may be varied. Of, course, a motor-generator set costs more to install than a synchronous converter of equal capacity and in addition it is not as efficient in operation as the converter, but in some cases the advantages gained

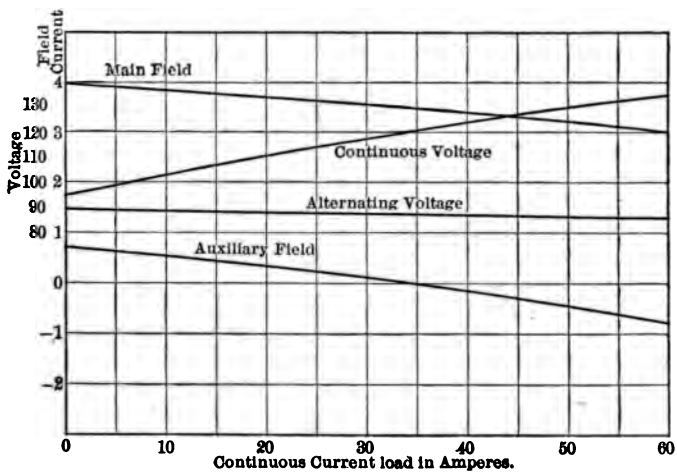


FIG. 255.—Curves Showing Compounding Possible on a Small Auxiliary Pole Synchronous Converter.

by an adjustable, continuous voltage offset these disadvantages.

**122. Vibrating Rectifiers—Rotating Commutator Rectifiers.** Many times a small amount of c-c. power is desired where only a-c. power is at hand; the charging of automobile storage batteries in the principal instance of this kind. Generally the amount of power desired is not sufficient to warrant the installation of a motor-generator

set or a synchronous converter, and some simple, cheap device must be used.

A vibrating rectifier has been designed and is on the market which furnishes a few amperes of uni-directional current at 10 volts or less. It consists of a polarized armature which is so pivoted that when acted on by

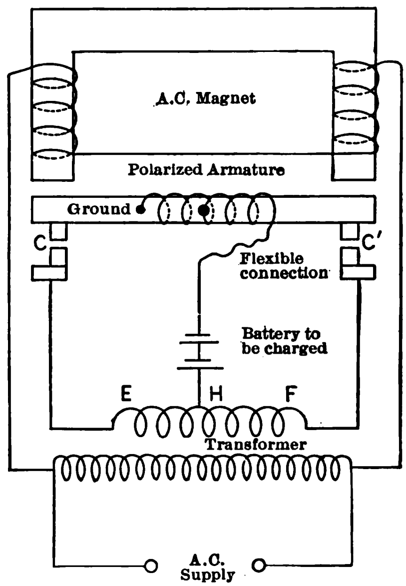


FIG. 256.—Connections of the Vibrating Rectifier.

an a-c. magnet it vibrates back and forth. A diagram of the connections is given in Fig. 256 and a cut of the device is given in Fig. 257. When $E$ is positive (with respect to $H$) the battery is charged through the contact $C$ and when $F$ is positive (with respect to $H$) the battery is charged through the contact $C'$. These contacts must be *adjustable* so that sparking may be eliminated. This

rectifier is small and simple to operate and should prove very useful. The battery cannot be connected improperly to the rectifier and cannot discharge if the alternating voltage fails; this makes the rectifier a very reliable piece of apparatus.

Another scheme for obtaining a small amount of c-c. power employs a commutator which is rotated by a small synchronous motor. The commutator has as many segments as the motor has poles and every other segment is connected together. Then each set of segments is connected

FIG. 257.—A Small Vibrating Rectifier, for Charging Storage Batteries from an a-c. line. Westinghouse Elec. and Mfg. Co.

through slip rings and brushes to the a-c. supply line. Brushes are placed on the commutator and the battery to be charged is connected to these brushes. Careful adjustment of the brush position is necessary to eliminate sparking to this rectifying device.

**123. Mercury Arc Rectifier.** Neither of the devices just described will operate well on circuits where much c-c. power is desired because sparking would take place at the contacts and the device would require constant attention when in operation.

But is is found that a tube filled with ionized* mercury vapor (the air having been exhausted from the tube), having mercury for one terminal and some such metal as iron for the other terminal *permits of the passage of current in one direction only.* If an alternating voltage is impressed on the two terminals of the tube, current will flow through the tube only when the mercury terminal is negative and the iron terminal positive. *In the tube itself, the current can flow from the iron to the mercury but cannot flow from the mercury to the iron.*

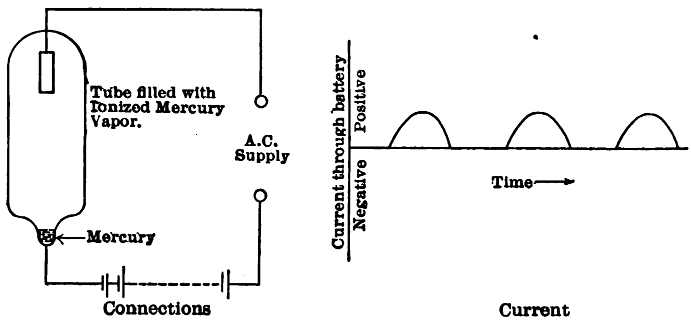


FIG. 258.—A Tube Filled with Ionized Mercury Vapor Acts like a Rectifying Valve.

*The Mercury Tube Acts Like a Check Valve.* If a mercury tube is kept filled with ionized mercury vapor it will therefore act as a *rectifying valve;* the current which flows through it will be pulsating as shown in Fig. 258. Although

* The term ionized is used to designate a gas in which the normal atom has been somewhat changed; a minute quantity of negative electricity (called an *electron*) has been freed from the atom and can move away from it. A gas in which this change has occurred conducts an electric current quite freely and it is said to be *ionized;* a gas in its normal condition conducts very poorly, in fact it is a good insulator. A gas may be ionized by the passage through it of an electric spark, by the influence of radium, etc.

such a pulsating current is not suitable for motors or lamps it would do very well for charging storage batteries. But the principal application of mercury arc rectifiers to-day is in connection with arc lamps and the current shown in Fig. 258 is not suitable for arc lamp operation.

*Use of Two Anodes.* By the addition of another positive terminal of iron and by using connections as shown in Fig.

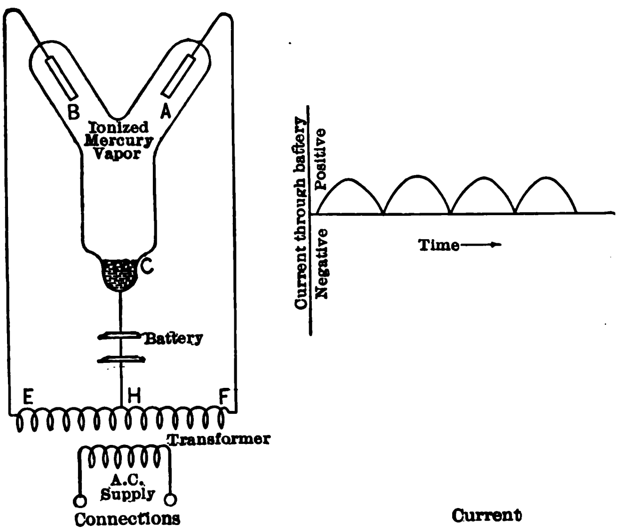


Fig. 259.—By the Use of Two Anodes it is Possible to Get a More Nearly Continuous Current.

259, it is possible to rectify every alternation, instead of every other one. The mercury terminal, called the **cathode,** is shown at *C* and the two iron terminals, called the **anodes,** are shown at *A* and *B*. The battery is connected between the cathode and a center tap *H* on the transformer. When *F* is positive with respect to *H*, current will flow through the tube and battery by the anode *A* and, when *E* is posi-

tive with respect to $H$, current will flow through the battery and tube by the anode $B$. The current through the battery will therefore have the form given in Fig. 259.

*Ionization of Gas Necessary for the Operation.* In order to operate as described above it is necessary that the tube be filled with ionized mercury vapor. If the mercury vapor is once ionized the current flowing through the tube will maintain the ionization but if the current ceases for a fraction of a second the vapor immediately becomes non-ionized and will not carry current. Hence a tube as represented in Fig. 259 would not maintain its ionization because at times 1, 2, 3, 4, etc., the current reaches zero value.

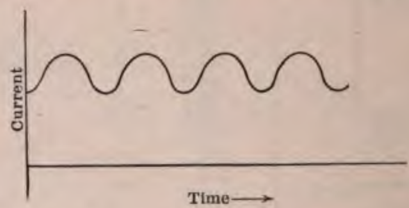


FIG. 260.—By Inserting Inductance in the Circuit the Current Form is Changed as Shown Here. Compare with Fig. 260.

*Maintenance of Ionization.* If, however, the transformer supplying the power to the tube is designed with considerable leakage (giving it self-induction) the current is changed from the form given in Fig. 259 to that given in Fig. 260; this current never reaches a zero value after the tube starts to operate, hence if the ionization in the tube is started by some method the current itself will maintain the ionization.

*Use of Starting Anode.* To start the ionization an additional anode, called the **starting anode** is provided. This consists of a pool of mercury close to the cathode as shown at $D$ in Fig. 261. When the tube is tipped slightly the mercury of $D$ runs over and makes contact with $C$.

If the starting switch $S$ is closed, a current will flow from $D$ to $C$, the magnitude of which is limited by the resistance $R$. Now, if the tube is tipped back, the mercury bridge connecting $C$ and $D$ is broken and the rupturing of the current causes a slight arc, *which is sufficient to produce the initial ionization of the mercury vapor.*

*Starting Resistance for Load.* To make the tube start readily a starting resistance $R'$ controlled by the switch $S'$, is first used as a load. After the tube has operated

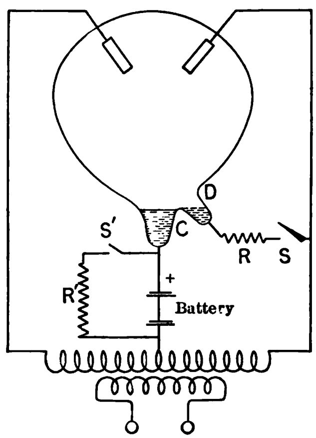


FIG. 261.—Connection Diagram for the Ordinary Mercury Rectifier, Showing Starting Anode.

through this artificial load for a few seconds, it becomes warmed and the battery may then be connected in the circuit and the starting resistance cut out. Of course, the switch $S$, controlling the starting anode $D$, is also opened as soon as the tube is operating properly.

**124. Application of the Mercury Arc Rectifier.** The two principal applications of the mercury arc rectifier are for charging storage batteries and for operating c-c. arc lamps from a-c. mains.

*Capacity of Mercury Tubes.* For charging storage batteries the tubes are made in various sizes with capacities of from three amperes to fifty amperes. For greater current capacities, the glass tubes are likely to overheat and so attempts have been made to utilize metal tubes immersed in oil to get proper cooling. However, the metal used must

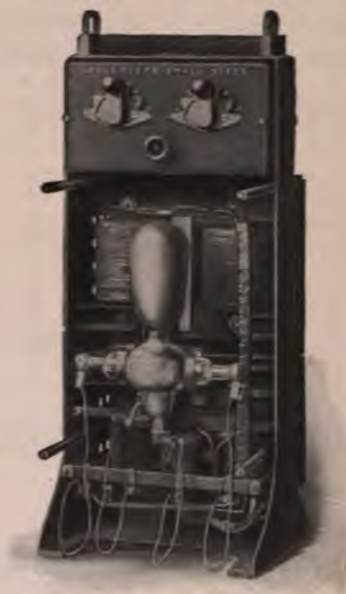

FIG. 262.—View of a Mercury Rectifier Outfit. Westinghouse Electric and Mfg. Co.

be one which does not amalgamate with mercury and iron seems the only suitable substance. But an iron tube will not hold a proper vacuum, so that tubes suitable for heavy currents are, as yet, in the experimental stage. If this problem is solved, it may be possible to substitute mercury tubes for synchronous converters for railway operation.

*Use of the Mercury Tube for Arc Lamps.* Flaming arc lamps, similar to the magnetite lamps, require continuous current for their operation. Series arc lamp systems are most conveniently operated from constant-current transformers, which of course, require an alternating-current power supply. The secondary of the transformer, instead of being connected to the lamp circuit directly, is connected through a mercury tube so that the arc lamps operate on a rectified current. The constant-current transformer operates to give practically constant current just as though the mercury rectifier were not in the circuit.

A view of a mercury tube outfit for charging storage batteries is shown in Fig. 262; this tube is designed to carry 30 amperes and the tube is generally guaranteed to give 400 hours life. As a matter of fact these tubes generally give more than 1000 hours life in actual operation; their failure is due to a change in the vacuum.

# CHAPTER XIII

## POLYPHASE POWER

**125. Polyphase Power Compared to Single-phase Power,** The polyphase system, whether two-, three- or six-phase, is evidently more complicated than the single-phase system, yet practically all electrical power systems are three-phase.

*Points of Superiority of Polyphase Power.* There are three important reasons for this fact. Polyphase apparatus is *cheaper to build* than single-phase apparatus of the same capacity; polyphase machinery (induction motors, synchronous converters, etc.,) has *better operating characteristics* than single-phase machinery; three-phase power transmission lines of a given kw. capacity and a specified efficiency of transmission, require *only three-quarters as much copper* for the line as would be required by a single-phase line.

**126. Polyphase Power for Transmission Lines.** If a given amount of power is to be transmitted, the two factors which are generally fixed are the voltage and the efficiency of transmission. We will compare the single-phase line with a three-phase line, the same amount of power to be transmitted over each and the power lost in each to be the same.

Let $P$ = the power to be transmitted;
$E$ = the voltage of the line, either single-phase or three-phase;
$I_1$ = the current, single-phase line;
$R_1$ = the resistance per wire of the single-phase line;
$I_3$ = the current, three-phase line;
$R_3$ = the resistance per wire of the three-phase line.

Then we may put

$$P = EI_1 = EI_3\sqrt{3},$$

so that

$$I_3 = I_1/\sqrt{3}.$$

The loss of power, single-phase line $= 2I_1^2R_1$;
The loss of power, three-phase line $= 3I_3^2R_3$.

These two losses must be equal if the efficiency of the two systems is to be the same, hence

$$2I_1^2R_1 = 3I_3^2R_3.$$

Putting for $I_3$ its equivalent, $I_1/\sqrt{3}$, we have

$$2I_1^2R_1 = 3(I_1/\sqrt{3})^2R_3,$$

or

$$R_3 = 2R_1.$$

If the cross-section of the wire for the single-phase line is $A_1$ and for the three-phase line $A_3$, we may put

$$A_3 = \frac{A_1}{2}.$$

There are *two wires* for the single-phase line and *three wires* for the three-phase, so that the total cross-section of copper for the single-phase line is $2A_1$ and for the three-phase line $3A_3$.

Hence, the total cross-section of the line for

Single-phase

$$= 2A_1,$$

and for three-phase

$$= 3A_3 = \frac{3A_1}{2}.$$

*Hence the three-phase line requires only three-quarters as much copper as the single-phase line.*

It may be proved that of all polyphase systems the three-phase requires less weight of copper than any other, and as it has just been shown to require less copper than the single-phase, the three-phase system is practically always used for power transmission systems.

**127. Polyphase Machinery Compared to Single-phase Machinery.** *The first cost* of a polyphase machine of a given kw. output is much less than that of a single-phase machine of equal output, and *the weight* of the polyphase machine is considerably less than that of the single-phase machine.

The reason for this may be seen by considering an alternator, of a given number of armature coils, etc. Let the safe current capacity of the coils be $I$ and the voltage generated by all the coils when connected in series (single phase winding) be $E_1$. The capacity of the alternator will evidently be equal to $E_1I$.

If now the coils are connected in three separate groups to form a three-phase winding the current capacity of each group will be $I$, as before, and the voltage of one group will be

$$E_3 = \frac{\sqrt{3}}{4}E_1.$$

The possible output of the machine will be

$$3E_3I = \frac{3\sqrt{3}}{4}E_1I = 1.30E_1I.$$

Hence the three phase winding, made up of the same coils used to form the single-phase winding, has a capacity which is about 30% greater than that of the single-phase winding.

If the coils were made up into a six-phase winding,

the possible output would be about 50% greater than as if the single-phase winding were used.

The single-phase induction motor is more expensive than a three-phase motor of the same capacity, not only because it weighs more but because some special starting devices must be furnished. As pointed out before, the single-phase motor has no starting torque.

The single-phase converter is practically never used; its capacity is much less than that of a three-phase machine of the same size, and also the single-phase machine has a great tendency to hunt. From the standpoint of *safe heating*, the three-phase machine would have a capacity more than 50% greater than that of the single-phase machine.

The synchronous motor is always wound for polyphase connection, not only because its capacity is thereby increased, but, also, because of the possibility of starting the polyphase machine as an induction motor. The single-phase synchronous motor would necessarily be equipped with some special starting device.

The efficiency of practically any piece of machinery is greater when designed for polyphase power than when designed for single-phase power.

*Hence we may conclude that polyphase machinery is preferable to single-phase machinery because of its less cost and weight and also because of its better starting and operating characteristics.*

**128. Grouping of Apparatus on a Three-phase System.** When a three-phase generator is used for supplying the current for a lamp load the three-phase system is generally divided into three separate single-phase systems. This is shown in Fig. 263. Three separate feeders are connected to the three-phase line and these feeders supply the neighboring districts.

*Balancing of Loads.* It is necessary to keep the loads on the three phases nearly equal; when unequal the load is said to be *unbalanced.* The unbalance in the current

taken by the different feeders results in more or less unbalancing in the voltages of the three phases and thus unsatisfactory illumination results.

If the load is unbalanced, the voltage cannot be regulated by such a device as the Tirrill regulator; *this can work on one phase only* and hence the voltage can be maintained constant on one phase only.

In grouping the apparatus on the three-phase system it is not only necessary to connect the same capacity of apparatus on each phase but the grouping must be done in such a way that the load is balanced at all times. It is not advisable to run single-phase motors from one phase

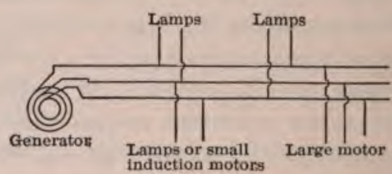


FIG. 263.—A Single Three-phase Distribution System.

of a three-phase system; too much unbalancing results unless the motor is very small.

**129. Polyphase Power Transformation.** It is not possible to transform a single-phase system into a polyphase system by means of ordinary transformers, but it is possible to transform one polyphase system into another, also to raise or lower the voltage of a given system with or without changing the number of phases.

*Two-phase to Three-phase Transformation.* The transformation of a two-phase system into a three-phase system (or vice versa) is accomplished by two transformers grouped according to the **Scott connection.** Fig. 264 shows how the connection is made. Transformer $A$ has a ratio of 1 to 1, and transformer $B$ has a ratio of 1 to 0.866, so that the voltage 1–4 is only 86.6% of the voltage 2–3. If it is desired

to change from a high-voltage two-phase system to a low-voltage three-phase system (or vice versa), it may be done providing only that the secondary voltage of $A$ is 86.6% that of $B$.

*Three-phase Transformation.* Three-phase transformation may be accomplished by one three-phase transformer or by three single-phase transformers. In special cases two single-phase transformers may be used for three-phase transformation.

The ratio in which the voltage is changed depends not only upon the ratio of the transformers themselves but

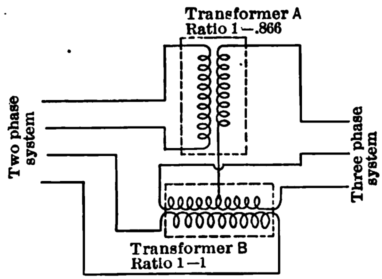


FIG. 264.—Connection of Transformers for Changing Two-phase Power to Three-phase Power or Vice Versa.

also upon the way in which they are interconnected. Supposing the transformers themselves have a ratio of one, the ratio of the transformation is as given below:

| Primaries Connected. | Secondaries Connected. | Ratio of Transformation. |
|---|---|---|
| Y | Y | 1 |
| Y | Δ | .612 |
| Δ | Δ | 1 |
| Δ | Y | 1.73 |

The significance of the terms Δ and Y and the method for making the connections was explained when discussing the armature windings of an alternator.

*Special Cases.* In addition to the four possible connections for three transformers given above, it is possible to use only two transformers. In the $\Delta$–$\Delta$ connection for instance, the transformation would be a true three-phase one, even though one of the transformers is removed.

This open $\Delta$, or " V " connection, gives balanced three-phase voltages, but two transformers so connected have a capacity of only 57% of the capacity of three transformers connected in $\Delta$. If, for example, two 1000 kv-a. transformers were connected in V, they would have a combined capacity (sometimes called " group " capacity) of only 1730 kw.; the addition of a third 1000 kv-a. transformer would raise the group capacity to 3000 kw.

In addition to the few simple connections shown, there are many more complicated groupings possible. With one scheme, called the " double $\Delta$," it is possible to operate a six-phase, synchronous converter from a three-phase supply line. Thus the efficiency of the three-phase transmission is combined with the increased capacity of a six-phase converter.

**130. Metering Power in a Polyphase Circuit.** In the polyphase circuit the power and power factor cannot be obtained as easily as for the single-phase circuit. In general, if a polyphase circuit consists of $n$ wires, it is necessary to have $n$-1 wattmeter readings in order to determine the power being supplied by the circuit. The connection of the wattmeters for a three-phase circuit is shown in Fig. 265. If the load is balanced and its power factor is unity, the two wattmeters will read alike, but if the load is unbalanced or the power factor is less than unity the two meters will read differently. In any case, whatever the balance and power factor, the sum of the two wattmeter readings gives the true value of the power.

*Circuits with Low-power Factor.* In metering three-phase power, however, caution must be observed as one meter may be reading negatively. This occurs if the

power factor of the load is less than 0.5; when the power factor is just 0.5 ($\phi = 60°$) one wattmeter gives zero indication. As the power factor decreases, this meter begins to deflect backward. To make it give a readable deflection its potential leads must be reversed; a reading is then taken and recorded as *negative* and the true three-phase power is the *difference of the two wattmeter readings.*

A convenient method of determining whether or not the reading of one meter should be recorded as negative consists in increasing the power factor of the load slightly

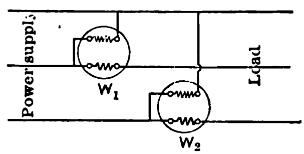


FIG. 265.—Connection of Wattmeters for Measuring the Power of a Three-phase Line.

and noting its effect on the readings of the two wattmeters. This increase in the power factor may be brought about by putting on an additional load which is non-inductive, such as lamps. *If the reading of one of the waitmeters decreases when the power factor increases, its reading should be recorded as negative.* In measuring the input of an induction motor running light, one of the wattmeters will generally give a negative reading; as the load on the motor is increased (thus increasing the power factor) it will be noticed that the reading of one of the wattmeters *decreases.*

# CHAPTER XIV

## AUXILIARY APPARATUS USED WITH ELECTRICAL MACHINERY

**131. Switches.** *Air-break Switch.* A switch is a device for easily opening and closing a circuit. The simplest type consists of a copper blade, hinged at one end and fitting tightly between two copper plates at the other. A wooden handle is fastened to the end of the copper blade, by which the switch is operated. It is styled a knife switch, or an air-break switch, because the current is ruptured in the air.

These switches are made in various sizes, from 25 amperes to several thousand amperes. The larger ones use compound blades, as the contact surface available on one blade would not be great enough to carry the large currents without over heating. The switches used for generators supplying power to lighting circuits are generally double pole, one blade being in each side of the line. Railway generators, however, have the negative side continually connected to the negative bus, and so to ground, so that these machines require only a single-blade switch in the positive line.

*Size of Switch.* The length of the blade depends upon the voltage for which the switch is designed; those to operate on a 600-volt circuit being considerably longer than those for a 250-volt circuit. This is due to danger of a short switch not opening a 600-volt circuit even though the blade has been pulled back as far as it will go.

*Arcing at a Switch.* Upon opening the switch an arc is formed and the arc may run down the blade as the switch

is opened and so hold over and burn from one post of the switch to the other. To prevent this disastrous arcing **quick-break switches** are sometimes used. These are so designed that the switch is opened by a spring, snapping the blade back very quickly.

*"Cutting" of a Switch.* Switches sometimes begin to "cut," especially in the hinge. This is caused by grit getting into the joint and wearing off little pieces of copper as the switch is opened and closed. Then the little bits of copper help this rubbing process until the blade is worn very rough in the hinge and so makes poor contact and is caused to overheat. As soon as "cutting" is detected, a switch should be taken apart and the rubbing surfaces smoothed down with a file and emery. A little grease in the joint will generally keep the rubbing surface in good condition.

*Oil-break Switch.* For voltages higher than 600 an **oil-break switch** is generally used. This type of switch opens in oil and the oil prevents the formation of a bad arc as the circuit is broken. Oil-break switches are generally used only on alternating current circuits, because the voltage of a continuous-current system is seldom greater than 600 volts while the voltage of an a-c. system is seldom less than 2300 volts. A high voltage a-c. circuit opens quietly with an oil switch, but an oil switch would not operate satisfactorily on a high voltage c-c. circuit.

By means of an oil-break switch a high-voltage a-c. circuit may be opened even when a high current is flowing through the switch. The arc which forms when the switch is opened is smothered by the oil and serious arcing or burning of the switch contacts does not occur.

The oil-break switch is generally located in an oil tank directly behind the switch board, and the handle by means of which the switch is opened is located on the front of the board. A link connects the handle and switch proper. A small oil-break switch is shown in Fig. 266.

*Disconnecting Switches.* A high-voltage, a-c. air-break switch is sometimes used but disastrous arcing will result if the switch is opened when carrying much current. They are used generally only as disconnecting switches; by means

Fig. 266.—A Small Manually-operated Oil Switch, Showing how it is Mounted on the Switchboard. General Electric Co.

of such switches a feeder may be disconnected from live buses, but this should be done only when the feeder is carrying no power.

*Remote-control Switches.* A switch which is opened directly by the operator is said to be a manually operated

switch. In large stations the oil switch may be opened by a small motor, the motor being located on the top of the switch tank. The current supply for the motor is controlled by a small switch placed conveniently for the operator; the oil switch itself may be far from the controlling switchboard. Instead of using a small motor for operating a remote-control switch, the action of an electromagnet may be used; in some types of switches (e.g., such as is used on many railway equipments) compressed air may be used to open and close the switch. It is the remote-control switchthat makes the compact, **remote-control switchboard** of a large modern power plant possible.

**132. Fuses.** When a machine or circuit is carrying more current than that for which it was designed, serious injury may result from overheating. The purpose of a fuse is to prevent such a possibility. A fuse consists of a piece of easily melted alloy, in the form of a wire or ribbon, connected in series with the machine or circuit to be protected. The size of a fuse is so selected that when a dangerous current is being carried by the circuit it is designed to protect, the heat generated by the $I^2R$ loss in the fuse is sufficient to melt it and so the circuit is automatically opened.

*Replacing a Fuse.* When a fuse is blown, the circuit in which it is connected should be opened by first opening the proper switch and then a new fuse may be inserted. A new fuse should not be inserted until it has been ascertained that the circuit is dead; neglect of this point is likely to prove dangerous to the operator putting in the fuse as the new fuse may blow (melt) while he is inserting it and so cause a dangerous burn.

There are several types of fuses in common use. The earlier type was the **string fuse,** which consisted merely of a piece of fuse wire inserted in the circuit by suitable clamps and screws. The disadvantage of this kind is that there is some danger of starting a fire when the fuse blows and throws melted lead around.

The **plug fuse** is designed to overcome this possibility; it consists of a short string fuse mounted in a porcelain plug fitted with a screw base like an incandescent lamp base. The cover to the plug is made of mica so that it may be seen whether or not the fuse has blown. The plug fuse is illustrated in Fig. 267.

*Cartridge Fuses.* It is not permitted by the National Board of Fire Underwriters to use plug fuses for currents greater than 30 amperes. For larger sizes the **cartridge fuse** must be used. This consists of a tube made of fiber, filled with borax, infusorial earth, or similar substances through the center of which the fuse ribbon passes. The two ends of the paper tube are fitted with copper ends to which the ends of the fuse are soldered. Short copper blades are fastened to these copper caps in the larger sizes and these fit into copper clips on the fuse block. When such a fuse blows, the arc is confined and smothered by the substance with which the fiber tube is filled.

FIG. 267.—A Plug Fuse, Such as is Used in the Different Circuits in House Wiring.

In order to detect whether or not such a fuse is blown a **tell-tale** is provided. This consists of a very small fuse, soldered to the copper terminals so that it is in parallel with the main fuse. This small fuse however, for a short way passes on the outside of the paper tube, so that it can be seen. When the main fuse blows of course the little one immediately melts and so gives evidence of the blowing of the main fuse. Such fuses are generally called N.E.C.S. fuses, meaning that they are designed in accordance with the National Electric Code Standard.

For high tension circuits, say several thousand volts, a special type of fuse is used, called an **expulsion fuse.** A long thin fuse is fastened in a tubular container (of some insulating material) open at one end. When the fuse blows

the gases in the container suddenly expand, and blow out of the opening. This explosive action of the hot gases effectually puts out the arc formed by the melted fuse. In Fig. 268 is shown a special type of such an expulsion fuse. The fuse container is mounted in a frame which serves as the blade of a switch; the switch is intended for use when the line which it supplies is carrying no load.

Fig. 268.—An Expulsion Fuse, Mounted in a Disconnecting Switch. This fuse is for use in a 15,000 volt line. General Electric Co.

Fig. 269.—The Disconnecting Switch of Fig. 268 Shown in the "Open" Position.

It is styled a **disconnecting switch.** Fig. 269 shows how the switch looks when open.

Before leaving the subject of fuses we must say a word regarding the practice of substituting copper wire, nails, etc., for fuses that have been blown, due to an overload

on the line. A fuse is used *to protect against fire, overheating of machinery, etc.* and when the fuse fails to work dangerous results may follow. If a fuse is replaced by a much larger one, or copper wire, etc., the circuit is no longer protected. An operator who replaces fuses by pieces of wire, etc., is just as foolish as a fireman who sits on the safety valve of his boiler and waits there for the boiler to blow up.

**133. Circuit Breakers.** In many kinds of service overloads occur quite frequently; this is especially true in railway work. If several cars start up at the same time or some cars start up just when two or three others are on an upgrade, the feeder supplying power for that section of the road is sure to be overloaded and, if it were fused, the fuses would be continually blowing, causing much work and annoyance to the operator. Also, during the time spent in replacing the fuses, the feeder would be dead and soon the cars would all be off their schedule time.

For this kind of service where overloads occur frequently and an operator is present, fuses are not used for protection; a switch that opens automatically when an overload occurs, called a **circuit breaker,** is used instead. The circuit breaker may open the circuit by an air break or by a break under oil. The oil-break circuit breaker resembles in appearance an ordinary oil-break switch, except that it has, of course, the automatic tripping and opening mechanism. These oil-break circuit breakers, when properly designed will successfully open high-voltage a-c. circuits through which thousands of kilowatts of power are being carried.

The air-break circuit breaker does not resemble a knife switch very closely as may be seen by reference to Figs. 270 and 271. This illustrates a double-pole breaker for a low voltage circuit of perhaps 100 amperes capacity.

*Use of Multiple Contacts on an Air-break Circuit Breaker.* The breaker shown in Fig. 270 is an air-break circuit breaker and it has three sets of contact surfaces; when the break is closed practically all of the current is carried through a

set of contacts made by a copper foil finger pressing against a copper block. When the breaker opens, these contact surfaces open and the current goes through another pair of copper contacts (not as carefully fitted as the first) and when these open, a final pair of contacts carry the current.

This last contact is made between two carbon blocks,

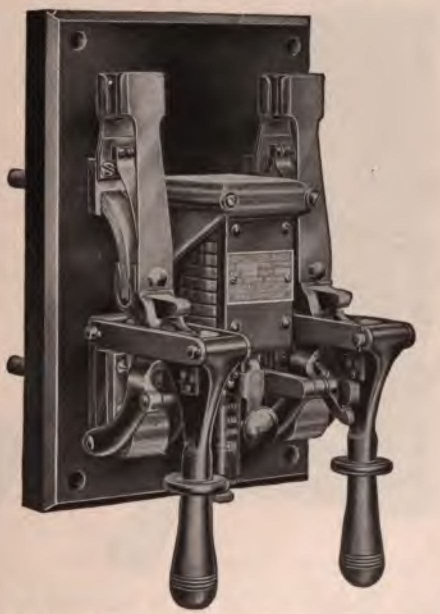

Fig. 270.—A Double-pole Air-brake Circuit Breaker for Use on a Low-voltage Circuit. General Electric Co.

the separation of which finally ruptures the current. The idea of thus breaking the circuit through a series of contacts is to preserve the main pair of contacts in good condition. If the current were ruptured by the main contacts, the arcing would soon spoil the contact surfaces. The arcing is really all done at the carbon blocks; when they are worn away a new pair may be put in.

The arm of the breaker is held in the "closed" position by a catch; it is tripped by the impact of a small plunger or similar device which is operated by a solenoid located in the breaker. This solenoid carries a current proportional to that which the feeder is supplying and when this current gets too large the solenoid lifts up the plunger, trips the

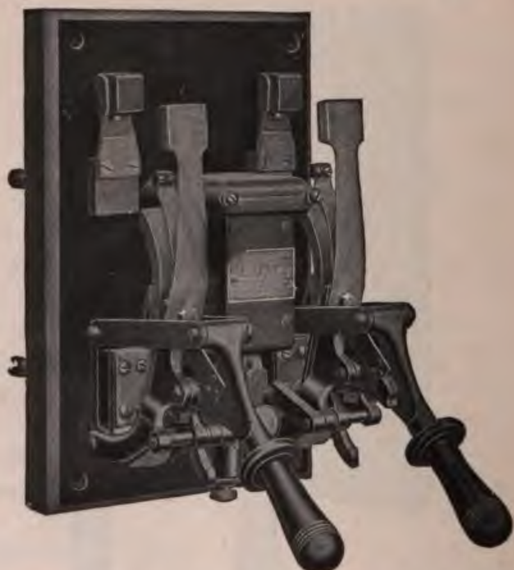

Fig. 271.—The Breaker of Fig. 270 is here Shown in the "Open" Position. General Electric Co.

catch, and a spring forces the breaker to quickly snap open. Fig. 271 shows the breaker in the "open" position.

*Procedure in Closing a Circuit Breaker.* Each breaker in a station has a knife switch or oil switch in series with it. When a breaker opens *it must not be closed until the switch in the same feeder has been opened.* The circuit breaker is for the protection of apparatus etc., and cannot operate if the attendant has hold of the handle, hence while *it is*

*being closed it cannot snap open.* If, however, the switch in series with it is opened first, then the circuit breaker closed, and then the switch closed, the circuit breaker is free to operate and protection against overloads is always obtained.

There is always an adjustment on a circuit breaker which fixes the current at which it opens the circuit. A certain breaker for example may be set to trip at any current between 45 amperes and 90 amperes.

**134. Overload, Time-limit Relays.** Any electric machine will stand an overload for a short time without suffering injury. A manufacturing company will generally guarantee that their machine will carry a 25% overload for two hours and a 50% overload for one minute.

*Heavy Overloads for a Short Time Not Dangerous.* Now in certain kinds of work the load on an electric machine is intermittent and for short periods of time there may be quite a heavy overload on the machine. But if the duration of this overload is short, the machine will carry it ssafely and it is not desirable to have the circuit opened by a breaker or fuse. But if this overload should continue too long, the machine would be injured, and it is thus evident that a fuse or circuit breaker could not properly take care of this kind of a load.

An **overload, time-limit relay** is designed to fit such a service. It is essentially a circuit breaker, the tripping coil of which is operated through a local circuit controlled by a relay. When an overload occurs the relay armature begins to move but the damping is such that a considerable time is required for the armature to move far enough to close the local circuit and thus trip the breaker. The time elapsing from the moment the overload occurs to the tripping of the breaker is adjustable by a valve in a dash-pot, or similar device. It is evident from this description that such a piece of apparatus as the time-limit relay just suits the needs of motors operating punch-presses, rolls, hoists, etc.

**135. Meters.** A complete description of the various types of meters used in electrical circuits would be out of place here and would take up too much space. We shall describe, in an elementary fashion, a few of the more important instruments and point out those qualities which a manufacturer tries to incorporate in his meters.

Meters may be divided into three general classes: **indicating, recording** and **watt-hour** meters. The latter are sometimes called **integrating** meters.

*Indicating Meters.* An indicating meter is one, the pointer of which deflects over a graduated scale, and so indicates at any instant the current or voltage in the circuit to which it is connected. It has no rotating parts and makes no record of the motion of its finger. These instruments show the operator how much current a feeder is carrying at any instant, or what voltage a machine is generating. From their indications the operator may properly adjust the voltage, re-distribute the load from one machine to another, etc.

They are subdivided into **switchboard instruments** and **portable instruments.** The first are fastened permanently on a switchboard and can generally be used only for indication on the machine or feeder to which they are attached. The portable meters are smaller and more compact than the switchboard instruments and are made for laboratory work, or for carrying out to different parts of a distributing system to read the current or voltage.

*Switchboard Meters.* A switchboard meter should be compact, have a large, well marked scale of uniform graduations (except in some special cases), have a large, black pointer on the end of the indicating finger, and should be well damped. Of course there are numerous other points to consider, such as permanency of calibration, freedom from temperature errors, etc., but we shall take up only those mentioned above.

On large switchboards, having many generators connected

to it, and supplying many feeders, the size of a meter is of prime importance. There may be on one switchboard a hundred or more meters and it is evident that if these


FIG. 272.—A Round-type Switchboard Ammeter. General Electric Co.

meters are not comparatively small, the switchboard must be very large and so difficult for one operator to manage. Also the expense for bus-bars, marble, copper feeders, etc., makes it advisable to keep the size of a switchboard as small as possible.

FIG. 273.—A Horizontal Edgewise Type Switchboard Meter. General Electric Co.

A round type of switchboard instrument is shown in Fig. 272 and in Fig. 273 is shown an edgewise type, having the scale horizontal. It will be noticed that the design of the meter has been carried out with the idea of getting compactness and still having a large, easily read, scale. The relative advantages of the round type and the edgewise types are much in discussion; which is the better seems to be an open question.

*Scale of a Meter.* The scale of an ammeter should be uniformly graduated, but sometimes it is advisable to have a voltmeter with a condensed scale on its lower ranges for the purpose of getting a more open scale in the range where it is always used. For instance a meter to be used on a

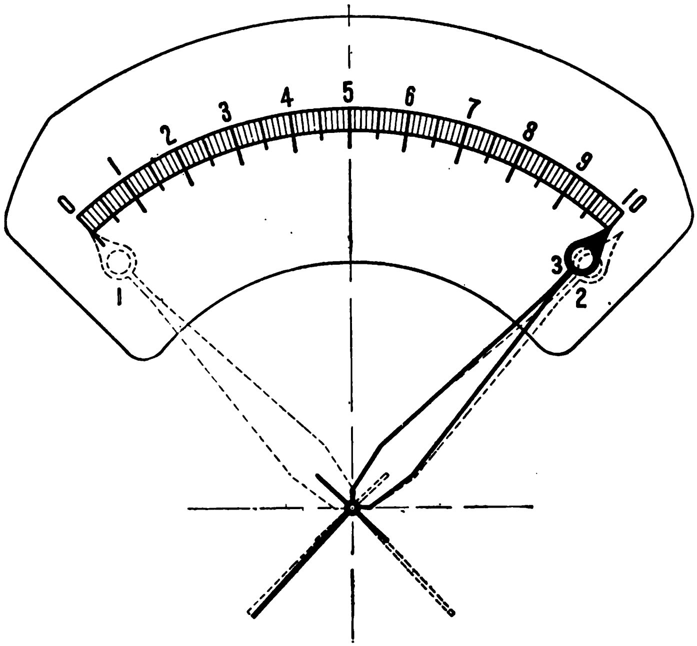


FIG. 274.—Diagram to Illustrate How Far a Well-damped Meter "Overshoots" its Proper Reading. Weston Electrical Instrument Co.

600-volt circuit would probably have a total range of 700 volts; from zero to 400 volts the scale might well be condensed as the meter is practically never used on these ranges. From 400 volts to 700 volts the scale could then be more open than if the scale was uniform throughout its range. The necessity for a clearly marked scale and large, easily-

seen, indicating pointer is apparent when it is remembered that one operator may have to notice continually the indications of a hundred or more of these meters.

*Damping of a Meter.* It is very essential that a meter be well damped; otherwise the finger will be continually oscillating back and forth and the operator must guess at the proper reading. Air vanes on the moving element, or the reactions of eddy currents in the moving element, serve to prevent the oscillation of the finger. If the meter is well damped it may be connected to a circuit and the needle will almost immediately come to rest in its proper position. An example of a well-damped instrument is shown in Fig. 274. On being connected to a circuit the finger overshot its proper position (3) by a very small amount (to position 2) and immediately dropped back to its proper position. It is not advisable to have the damping designed so well that the meter overshoots not at all because then the operator would have difficulty in ascertaining whether or not the meter were sticking and so not indicating accurately.

Fig. 275.—A Portable Type Voltmeter, for Laboratory Use. Weston Electrical Instrument Co.

*Portable Meters.* The portable type of meter differs from the switchboard type in that it is generally more accurately calibrated, has a more accurate and finely divided scale, and has a very thin indicating pointer. A switchboard instrument which indicates with an accuracy of 1% is generally plenty good enough; for laboratory tests, however, much higher accuracy is generally required. A common type of portable laboratory voltmeter is shown in Fig. 275; it is mounted in a box and fitted with a carrying handle.

*Recording Meters.* A recording meter is much used in station work. Its moving element carries a pen which draws a curve on a paper strip which is fed under the pen by suitable clock work. A very fine type of recording meter is shown in Fig. 276. The moving element is a kind of magnetic balance which carries the glass pen back and forth

FIG. 276.—A Recording Meter. Its records serve for checking station efficiency, uniformly of load, etc. Westinghouse Elec. and Mfg. Co.

over the paper strip as the current through the instrument varies.

*Value and Importance of Records.* By inspection of the curve traced by such an instrument the station superintendent can tell at a glance just what the load on his station has been, what its maximum and minimum values were and when they occurred. Or, if the record is from a voltmeter,

it serves to show how well the operator has maintained the voltage constant. These meters are excellent for keeping the operator at his task as they infallibly indicate any variations in the station voltage.

*Watt-hour Meter.* An integrating meter or watt-hour meter consists essentially of a little motor, the armature of which is attached to a train of gears which operate fingers over properly graduated dials. *The motor is so designed that its speed is directly proportional to the power being supplied through the line to which it is attached.* Hence the number of revolutions through which it turns is proportional to the power flowing through the meter multiplied by the time during which this power flows. But the product of power × times = energy, and so the number of revolutions of the meter is proportional to the amount of electrical energy that has passed through it.

FIG. 277.—A Thomson Watt-hour Meter. The case has been removed to show the working parts. General Electric Co.

The train of gears is so designed that the indications of the fingers on the dials are in kilowatt-hours or multiples thereof. As just explained this type of meter gives a reading proportional *to all the energy that has passed through it* and from this fact it derives its name of "integrating" meter; the name watt-hour meter, however, is preferable. The Thomson watt-hour meter is illustrated in Fig. 277 and Fig. 278 shows a watt-hour meter for use in a-c. circuits.

*Frequency Meter.* In the operation of alternating current systems it is necessary to maintain the frequency of the system constant. For the purpose of showing immediately if this is so the **frequency meter** has been designed.

Various types of frequency meters have been designed, one of the more common types being the **vibrating reed frequency meter.** A series of steel reeds, of different natural periods of vibration, are so mounted that they are all attracted by an electro-magnet, which is connected across a line the frequency of which is required. Although the alternating magnetic field acts on all of the reeds *only that one whose natural period of vibration is the same as that of*

FIG 278.—A Watt-hour Meter for Use on a-c. Circuits. Westinghouse Elec. and Mfg. Co.

*the magnetic field* will vibrate appreciably. The natural frequency of the different reeds is marked on the face of the meter; by noticing which reed is vibrating the operator can tell at a glance the frequency of the line.

Another type of frequency meter consists of a set of coils connected to the line through inductances and resistances and a movable iron vane which carries a pointer. combination of coils is such that the iron vane assumes

different positions when connected to lines of different frequency. Such an instrument is shown in Fig. 279.

*Power-factor Meter.* The power-factor meter is an instrument which is calibrated to read directly $\cos \phi$, the power factor of the load to which it is connected. Such an instrument is very useful for getting the proper adjustment of field current on a synchronous converter, synchronous motor, etc. In a station where several alternators are operating in parallel this instrument is used to show whether


FIG. 279.—A Frequency Meter, with the Outer Case Removed to Show the Internal Construction. General Electric Co.

the different generators are all operating with proper field excitation. If one alternator shows a low power factor compared to the others, its field excitation is either too high or too low. By watching the power-factor meter the operator can immediately bring the field current to its proper value.

As the power factor of a circuit depends upon the phase relation of the voltage and current in the circuit, there must

be two sets of coils in a power-factor meter, just as there are two coils in a wattmeter.

The stationary coils of a power-factor meter produce a magnetic field which is in phase with the current in the circuit. The movable coil, which is connected across the load circuit (just as the potential coil of a wattmeter is connected across the circuit), produces a magnetic field the phase of which depends upon the phase of the line voltage. The position which the movable coil takes under the action of the two magnetic fields, depends upon the phase relation of the voltage and current. The pointer which the movable coils carry, moves over a scale calibrated directly in the values of $\cos \phi$.

**136. Switchboards.** Originally the switchboard was a very crude affair, a wooden rack on the front of which were mounted the switches and fuses necessary for the operation of the plant. To-day the switchboard is probably the most important part of a generating plant; if an accident happens at the switchboard, the whole plant may be crippled.

The switchboard is the place to which the electric power from the generators is supplied and metered and thence distributed to the outside system through a group of feeders. On it are located all the switches, meters, and protective devices of the plant and from it the operation of the whole plant, both inside and outside the power house is controlled.

*Panels.* A modern switchboard is divided into a number of *panels;* each panel serves for the control either of one generator or of a feeder or group of feeders. They are styled the *generator panels* and *feeder panels;* in addition there may be panels for exciters, recording meters, etc.

*Construction of a Switchboard.* The material of which the board is made must be a good insulator and of pleasing appearance; slate is sometimes used in cheap boards but generally a high grade of marble is employed. The marble is a better insulator than slate (which is likely to have

streaks of conducting mineral matter through it) and is much finer in appearance; of course it costs more than slate. The panels may be from 18″ to 24″ wide and perhaps 6′ high. They are supported by a frame work of structural steel anchored to the floor and wall of the station house.

*Bus-bars.* Behind the whole length of the switchboard run a set (two or three) of heavy copper bars, called **bus-bars,** or sometimes merely **busses.** The general arrangement of the board is to have all the generator panels on one side and the feeder panels on the other; the bus-bars then convey the total power of the station lengthwise along the board. For this reason they have a very large cross-section. They, as also the rest of the connecting bars and wiring on the back of the board, are supported by porcelain channels and cleats fastened to the steel frame work of the board.

*Arrangement of Panels.* Each generator is connected through its respective circuit-breaker, ammeter, and switch to the bus-bar at a generator panel and each feeder is connected to the bus-bars through its ammeter, circuit breaker and switch. By having all generator panels on one end of the board and all feeders on the other end, the addition of more generators or feeders is easily accomplished without disturbing the arrangement of the board; the proper number of panels may be added at either end of the board.

At the center of the board between the generator and feeder panels is located the **station output panel** on which are located the recording and watt-hour meters that show the total power output of the station. By daily records of these meters and of the records of the customers' meters, the station manager may obtain an idea of the efficiency of his system, i.e., the ratio of the amount of power sold to customers to the total power sent out of the station. If this ratio is low he must improve it by better insulation of the outside lines, checking the accuracy of the customers' meters, etc.

The front and back views of a single panel switchboard, showing meters, oil switch, supporting frame-work of iron pipe, etc., are shown in Figures 280 and 281.

FIG. 280.—Front View of a Single Panel Switchboard; the Meters, Handle for the Oil Switch, are Shown Here. General Electric Co.

FIG. 281.—Back View of Panel Shown in Fig. 280; the Oil Switch, Iron Pipe Support, etc., are Shown Here. General Electric Co.

Switchboards for large alternating-current stations are different from that shown above. The bus-bars of an a-c. switchboard are generally of high voltage, perhaps, 11,000 volts. The circuit breakers and switches must be of the oil immersed type and are cumbersome and difficult to arrange well on the back of a switchboard. As the oil switches are generally motor operated, it is of no advantage to have them at the switchboard, so they are generally located in some fire-proof recess out of the way.

The control of these motor-operated switches is carried to the **master switchboard,** generally quite small compared to the main switchboard. From this master control board, the chief operator can manipulate all the machines and switches in the station. The master control board is generally located in a quiet part of the station but is so placed that the operator has in full view, all of the machines and apparatus which he controls. The chief advantage of the remote control switchboard rests in the possibility of one operator carrying out all the necessary switching in the station; the responsibility is thus centralized and fewer accidents, due to improper switching, take place than in a station where several operators are required.

Another advantage is due to the isolation of the control board; if an accident occurs in the station the chief operator can carry out the proper switching operations without being influenced by the confusion and noise in the generator room. Small signal lamps of different colors, show the operator what machines are running, what feeders are alive, what switches are open, etc. In fact the operation of the whole station is clearly shown and easily carried out by one man working on the master control board.

# CHAPTER XV

## OPERATION AND CARE OF ELECTRIC MACHINERY

**137. Location.** In selecting the proper location for an electric machine the two principal points to be kept in mind are *first*, a machine must be kept dry and *second*, it must be kept free from dust and dirt. If these two requirements are not satisfied a motor or generator will soon deteriorate and develop faults.

*Effect of Moisture.* If moisture is allowed to accumulate on or around a dynamo-electric machine, the machine will very soon be more or less **grounded.** A machine is said to be grounded when any part or parts of the electric circuits are connected to the frame work (field casting, armature core, etc.) Such a grounding of the winding may be very dangerous for the operator; in the case of a high-voltage generator or motor it might cause a fatal shock if the operator should come in contact with the frame work when he is standing upon a concrete floor or some other partially conducting surface. This point will be more fully discussed in the section on *faults.*

Beside the possibility of grounds, there is that of the windings becoming short circuited due to moisture. This is especially likely to occur by the development of *two grounds,* on different parts of the windings. A machine which develops a short circuit is sure to be seriously damaged by burning unless the fault is at once discovered and removed.

*Effect of Vibration.* Of course, in choosing the location for a machine care must be exercised that a *firm foundation*

can be provided. Even though an electric machine is very well balanced before leaving the factory it is sure to vibrate more or less when running, unless it is fastened to a solid bed of some sort. If a machine is allowed to vibrate when in operation, there is likely to be sparking at the brush contacts, owing to the fact that the brushes make poor contact with the vibrating commutator; the vibration may also make the bearings heat excessively.

*Effect of Dust and Dirt.* Any continuous-current machine is almost sure to develop commutator trouble if it is operated in such a location that dust or dirt can fall on the commutator. The dirt will work into the bearing surface of the brush, producing a rough surface and spoiling the commutator surface by scratching and undue wear. Also it is likely to work into the insulation between the commutator bars and produce a partial short-circuit between adjacent bars. When a partial short-circuit occurs, it soon develops into a complete short-circuit and the coil which is attached to the two segments likely to burn out.

*Faults Tend to get Worse.* A point for the operator to keep constantly in mind is that nearly all of the faults developed by electrical machinery *tend to aggravate themselves if not immediately remedied.* Thus a slight roughening of the commutator will produce but imperceptible sparking; unless, however, the rough spot is removed (the cause also removed) the commutator will soon be unserviceable.

If it is absolutely necessary to run a machine in a room where dust accumulates, as, for example, in a cement mill or flour mill, an *enclosed type of machine* should be installed if possible. This type of machine is completely closed by end pieces being fitted to the sides of the yoke; the bearings are fitted into these end pieces. The armature, commutator, etc. are thus completely shut in so that dirt and dust can collect only on the outside of the machine. where it can do but little harm. (All railway motors, e.g., are of this enclosed type, so that the working parts

are kept free from the dust and moisture with which the car truck gets covered.) If it is not possible to use an enclosed type of machine, the attendant must exercise special care in keeping the commutator clean and must blow the dust out of the windings by means of a bellows whenever the machine is shut down.

**138. Precautions in Starting a Machine.** After a machine has been properly installed a thorough inspection must be given *before the machine is started.* The operator must look over the machine very carefully to see that there are no mechanical or electrical faults which would injure the machine as soon as started.

The machine should be thoroughly blown out by a bellows, so that any dust, dirt, chips, etc. which may have collected in the interstices of the windings and various parts, may be cleaned out.

*Tightening of Parts, etc.* All parts of the machine should be thoroughly tightened; a pole may pull loose from the yoke very soon if its fastening bolts are not drawn up snug; the same precaution holds with respect to the pole shoes and any other parts held together by bolts. Care must be observed to see that there is nothing in the air gap; a small nut, nail, etc., in the air gap may cut the armature winding badly when the machine is started.

*Bearings.* The machine must turn freely in its bearings and the oil-rings must be picking up the proper amount of oil. This latter point is extremely important; oil-ring bearings operate so reliably in general that they receive less attention from the operator than they really require. The oil used in the bearing should be the best grade of machine oil; if too thick, it will not flow freely through the oil ducts in the bearing and if too thin it runs out too quickly and there is not a sufficient layer of oil between the shaft and bearings for proper lubrication. The bearings must be thoroughly cleaned from dirt, grit, etc.

**139. Spacing the Brushes.** A machine may spark badly at the brushes no matter how well the brushes may have been ground and how smooth the commutator may be. This may be due to the *improper spacing of the brushes.* Of course many other causes may exist which produce sparking; some of them have been taken up already and they will be all grouped together in the tabulated list of faults, which is given on a following page.

If a *two-pole* machine is considered it is seen at once that the brushes should be spaced 180° apart on the commutator; on a *four-pole* machine they should be 90° apart, etc. On the earlier types of machines, where the interpolar space (space between the adjacent tips of consecutive poles) was large, the necessity for setting the brushes exactly the right distance apart did not exist. Around one side of the commutator of a two-pole machine there might be 49 segments between brushes and around the other side perhaps 51 segments and still there might not be excessive sparking.

*Proper Spacing Important on Commutating Pole Machines.* On the more modern machines, however, especially on machines having commutating poles, the brushes must be set exactly the right distance apart. On a high voltage synchronous converter, if the spacing between one set of brushes is greater than that between another set by half the width of one commutator segment, bad sparking is likely to result. In addition to the sparking trouble, the armature of a machine on which the brushes are improperly spaced is very likely to overheat, even though the machine is not delivering full-load current to the outside circuit.

*Uneven Spacing Produces Sparking.* The sparking, with unequally spaced brushes may be due to either of two causes, or both. As we have shown before, the armature winding of any continuous current armature consists of two or more circuits in parallel, the lap wound armature

having as many paths as there are poles, and the wave wound armature always having two paths. It may be that there is a greater e.m.f. induced in one path than in another if the brushes are unequally spaced. But if the several paths are in parallel and one path has a greater e.m.f. than the others, then this path will force current to flow through the others even though there is no load on the outside circuit.

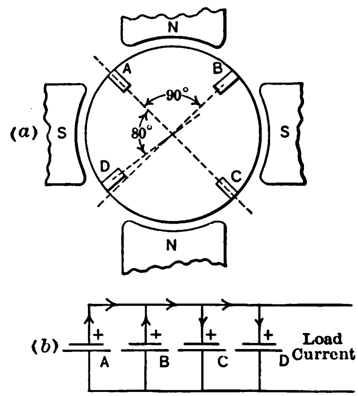


FIG. 282.—Brushes Unevenly Spaced; the Armature is Then Similar to the Battery Circuit Shown in Sketch (*b*).

*Cause of the Sparking.* Consider the case shown in Fig. 282 (*a*) where the brushes *A*, *B* and *C* are correctly spaced, 90° apart, but *D* is misplaced so that the distance *A–D* is 80° and the distance *D–C* is 100°. The paths *A–B* and *B–C* generate the normal rated voltage of the machine while the two paths *A–D* and *D–C* generate something less than this value as there are less effective inductors in the latter two quadrants than in the others.

The electrical conditions in the armature are then the same as those shown in Fig. 282 (*b*) in which figure the cells *A* and *B* are supposed to develop a higher e.m.f. than

the cells $C$ and $D$. Even though there is no load on the battery, the load circuit being open, there will still be current flowing in the different cells as indicated by the arrows. The amount of current which will thus flow in the different paths of the armature depends upon the inequality of the voltages in the different paths and upon the resistance of the armature. In large machines this resistance is very small and so, on large, high voltage generators, it is very important that the brushes be spaced exactly right.

If the brushes on a commutating-pole machine are unequally spaced, it is impossible to eliminate sparking at all brushes because when one brush or set of brushes is in the correct position with respect to the commutating poles, some of the other brushes cannot possibly be placed properly, because we have supposed the brushes unequally spaced while the commutating poles are always spaced equally from each other. We have previously shown that a commutating pole machine is very sensitive with regard to the proper placing of the brushes with respect to the commutating poles.

*Testing for Spacing.* The easiest way to obtain equality in spacing is to measure the total circumference of the commutator by laying a tape or strip of paper around the commutator surface under the brushes. This distance, divided by the number of brush studs, is the proper spacing to use in measuring *from the toe of one brush to the toe of the next brush.*

**140. Fitting the Brushes.** The brushes must be thoroughly "sanded" to fit the commutator. This task requires a deal of time on the larger machines and must be done carefully. The proper method is shown in Fig. 284. *Sandpaper* (never emery cloth) must be used for this purpose. The sandpaper is torn into strips slightly wider than one brush and a strip is inserted between the brush to be fitted, and the commutator surface, the rough side

of the paper being outside. (It is supposed that the brushes have been adjusted for the proper tension of about 1.4 lbs. per sq.in. of contact surface.) Then with the strip of sandpaper held tightly against the surface of the commutator, it is worked back and forth, grinding

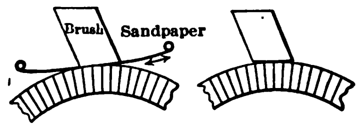


FIG. 283.—Sandpaper Held Improperly and Resultant Shape of Brush.

the under surface of the brush to a shape that just fits the commutator.

*Improper Fitting of Brushes.* While the brush is being ground it is *extremely important* that the sandpaper be so held that it lies tightly against the commutator for at least an inch or two both ahead and behind the brush, otherwise

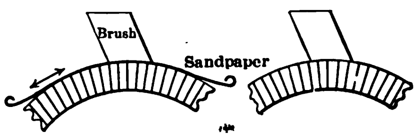


FIG. 284.—Sandpaper Held Properly and Resultant Shape of Brush. The sandpaper should be allowed to grind the brush only when being pulled in the same direction as that in which the commutator ordinarily runs.

the brush will be ground in such a fashion that only the center part of it fits on the commutator, the toe and heel having been cut away by the sandpaper. Fig. 283 shows the sandpaper improperly held and the resultant shape of the brush. The surface of such a brush actually touching the commutator surface is very small and, when a load is

put on the machine, excessive heating will develop at this point. Fig. 284 shows how the sandpaper should be held and also how the brush when so ground fits the commutator over its whole cross-section. While the brush is being ground the sandpaper should be drawn under the brush only in the same direction as the machine is designed to run.

*Use of Emery Cloth.* If emery cloth is used instead of sandpaper, two faults are likely to develop. The abrasive material used in making the rough surface of the emery cloth is a partial conductor and small particles of it are likely to become imbedded in the insulation separating the copper bars thus producing a partial short circuit of the commutator. Or small particles of it may become imbedded in the contact surface of the brush and so, when the machine is in operation, may produce severe cutting (roughening) of the commutator surface because the emery grains are extremely hard.

**141. Effect of Unequal Air Gaps.** The inequality of voltage in the different paths will also occur even when the brushes are properly spaced, if the *air gap under some poles is less than under others.* As there is the same magnetizing force on all field poles (same number of turns and same current) that magnetic circuit having the smaller air gap will have the smaller reluctance and therefore the greater flux. Therefore the inductors lying under those poles having the smaller air gaps will generate a greater e.m.f. than the inductors lying under the poles with a larger air gap. Hence those paths in the armature lying under the poles with the smallest air gap length will generate a greater e.m.f. than the other paths and so current will flow from one path to the other in such an armature, even though no load is being supplied by the machine.

The inequality in air-gaps is also likely to produce heating in the bearings. That pole under which the magnetic field is most dense will exert a greater pull on

the armature core than the others, resulting in excessive pressure on the bearing and thus tending to produce a hot bearing.

*Development of Unequal Air Gap by Wear of Bearings.* This inequality in air gap may not exist when the machine is sent out from the factory but may develop if the bearings are allowed to wear down to an appreciable extent. This allows the armature to drop slightly, shortening the air gap for the magnetic circuits on the lower side of the armature and lengthening it for those above.

This same difficulty occurs if one field coil becomes short circuited from any cause. The inductors under the pole with the short-circuited coil will generate practically no voltage.

**142. Faults Occurring in Electrical Machinery.*** The difficulties which may be encountered in the operation of electrical machinery are tabulated below and an explanation as to why they occur and how they may be remedied, according to table on p. 437.

**1.** A rough or dirty commutator always produces sparking at the brushes. The causes for the roughening of a commutator have been given before. When the roughening exists to a slight extent only, it may be remedied by polishing the surface of the commutator with sandpaper. If the machine is a motor, all brushes but one pair should be lifted out of the holders; the one pair left in contact with the commutator will carry enough current to run the motor with no load.

* In making up the following table the author had in mind principally continuous current machinery, because faults are so much more likely to develop on c-c. than on a-c. machinery. There is generally no commutator on an a-c. machine and it is much more rugged than a c-c. machine. For this reason trouble is seldom experienced unless a machine is actually burned out or damaged very seriously. In this case the machine would of course be sent back to the factory.

Faults likely to occur in the operation of c-c. machinery

- A. Sparking at the commutator
  1. Rough surface
  2. Brushes in the wrong position
  3. Insufficient brush tension
  4. Poorly fitted brushes
  5. Armature overloaded
  6. Vibration of the machine
  7. Short-circuited coil
  8. Open-circuited coil
  9. Unequal brush spacing
  10. Unequal air gaps
  11. Poor design
- B. Heating
  12. Bearings
  13. Commutator
  14. Armature
  15. Field coils
- C. Generator fails to build up
  16. Open-field circuit
  17. High resistance in the field rheostat
  18. Dirty commutator
  19. Wrong position of the brushes
  20. No residual magnetism
  21. Field connected incorrectly to the armature
  22. Speed low
- D. Motor fails to start
  23. Supply line dead
  24. Fuses blown
  25. Field or armature circuit open
  26. Too much resistance in the field rheostat
  27. Too much starting torque required by the load

The motor is then run at a low speed and the surface first smoothed by coarse sandpaper held on the commutator surface by a block of wood, the face of which is perfectly flat. The sandpaper is moved slowly back and forth across the commutator as it revolves and this process is continued until all rough spots have been removed. Then finer sandpaper may be used in a similar fashion to polish the surface and, finally a commutator stone should be used, or else fine sandpaper may be used with a small quantity of machine

soon, the short-circuited coil will be burned out. Sometimes the short circuit occurs by a thin copper bridge being spun over the mica insulation between the two copper segments to which the ends of the coil are attached. Or the insulation may have broken down on the armature where the end connections of the coils cross each other.

**8.** An open-circuited coil produces very vicious sparking every time the coil passes under a brush. The commutator bars to which the faulty coil is connected soon become very badly burned and, if the machine is allowed to run any considerable time with an open-circuited coil, the bars to which it is attached burn away so badly that it becomes necessary to turn down the whole commutator before sparking can be prevented, even though the faulty coil has been repaired. The method of locating a short-circuited or open-circuited coil will be described in the last section of this Chapter.

**9.** This trouble has been discussed on a preceding page. The brushes may be tested for even spacing by measuring accurately the distance around the commutator surface, between brushes. If this proves to be uneven, the spacing may be changed by rocking the brush holder on the brush holder stud.

**10.** The air gap may be accurately measured by a tapered steel wedge. This wedge is chalked and then pushed into the air gap as far as it will go in a direction parallel to the shaft. The pole rubs the chalk off and so the distance the wedge was inserted can be easily determined and its width at this point measured by a micrometer caliper. This distance must be practically the same for all poles; if it is not, a thin piece of sheet iron may be inserted between the poles and yoke, where the air gap is too long. This is generally called "shimming-up the pole."

**11.** When discussing the subject of commutation, it was shown that when the coefficient of self-induction of the armature coil was too high or the width of the brush

removed from the field frame and swung in a lathe for turning the commutator.

**2.** If the brushes are in the wrong position they will all spark, but the difficulty is easily overcome by manipulation of the brush yoke rocker. On some machines, not equipped with commutating poles, the brush position must continually be changed as the load changes if sparkless commutation is desired.

**3.** The brush tension should be between one and one and a half pounds per sq.in. of contact area. If the tension is not enough, the brush will not " follow " the commutator and if the tension is too great, the commutator heats because of excessive loss due to friction. Loosen or tighten the springs used for holding the brush on the commutator.

**4.** These result through the unskilful fitting of the brushes or by a faulty brush having hard spots in it and so wearing unevenly. This trouble may be detected by a close examination of the wearing surface of the brush, after the brush has been taken from the holder. The surface should be smooth and polished all over; if the wearing surface is polished only in spots, it indicates a non-homogeneous brush and a new one should be substituted.

**5.** A machine not equipped with commutating poles will always spark when overloaded, while a commutating pole machine will not do so unless the overload is very excessive. Inspection of the switchboard ammeter will locate this trouble and if the meter indicates an overload, part of the load should be taken off.

**6.** If a machine vibrates to any extent, it is likely to prevent the brushes from making firm contact with the commutator surface and sparking occurs. The machine must be put on a more solid foundation and balanced better to get rid of this trouble.

**7.** A short-circuited coil will always produce bad sparking at the brush contact every time the short-circuited coil passes under a brush. Unless the trouble is remedied very

soon, the short-circuited coil will be burned out. Sometimes the short circuit occurs by a thin copper bridge being spun over the mica insulation between the two copper segments to which the ends of the coil are attached. Or the insulation may have broken down on the armature where the end connections of the coils cross each other.

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**11.** When discussing the subject of commutation, it was shown that when the coefficient of self-induction of the armature coil was too high or the width of the brush

too small or the speed of the commutator too high, it would be impossible to obtain sparkless commutation. These points are well understood by designers so that such a cause of sparking is not likely to exist. If it does, the operator can do nothing to remove it and the machine must be turned back to the factory as being improperly designed.

**12.** Heating of the bearings is generally due either to lack of oil, to the poor grade of oil used, or else to the dirt in the bearing. The attendant should keep constant watch of all bearings and if one begins to heat excessively the cause should immediately be discovered and removed. If this is not done, the bearing is likely to get hot enough to melt the Babbitt metal lining and then the machine is very likely to be injured seriously. If the Babbitt metal runs out, the armature may drop enough to rub on the pole faces and tear the binding wires loose etc., and the shaft is likely to be scored badly where it goes through the bearing.

If the bearing begins to get too hot, it is quite probable that its temperature will continue to increase until the lining melts. This is due to the fact that the excessive heating of the box thins the oil to such an extent that it no longer affords the requisite lubrication. If a bearing is discovered dangerously hot, oil (preferably heavy, such as cylinder oil) should be poured liberally into the holes on the top of the box, the shaft should be cooled by pouring water on it close to the bearing when possible (using care to keep the windings dry) and the machine should be kept turning slowly.

*Water should never be poured over the box and the machine should never be allowed to stop turning* until the bearing has cooled sufficiently to be at a safe temperature. If these two precautions are not heeded the shaft is likely to "freeze" in the bearing, i.e., the bearing metal solidifies tight to the shaft just as solder does in a soldered joint. When this

happens, it takes a skilful mechanic to get it off; it should not be attempted by the machine operator as the shaft is likely to be spoiled by scratching and scoring in removing the box.

**13.** If a commutator is allowed to become too hot, all of the coil connections are likely to be melted loose from the commutator bars. The over-heating of a commutator may be due to excessive brush pressure, sparking at brushes, too high a current density in the brush contact surface, or having improper lubrication.

If too high a current density is used in the brushes, either larger brushes must be employed or the rating of the machine must be decreased. A commutator often gets hot because of insufficient lubrication at the brush contact surface; most brushes are made self-lubricating but a little machine oil applied to the surface of the commutator with a piece of rag often helps to keep the commutator in good condition and stops heating and sparking. All superfluous oil must be carefully removed from the commutator surface by a clean rag or it will soon result in a dirty commutator and, therefore, in sparking.

**14.** The armature may become too hot either because of excessive core loss or excessive $I^2R$ loss. If the first cause exists, the core has been improperly constructed or else the machine is operating at a higher voltage than that for which it was designed. If the armature heats because of a high $I^2R$ loss, there may be a short circuited coil or else the machine is carrying too much load. In either case the remedy is evident.

**15.** Excessive heating of the field coils is likely to occur only if they are forced to carry more current than that for which they were designed. One field coil may become short circuited and thus cut out of the circuit; the rest of the coils will then carry more than the normal current. This fault very seldom occurs.

16. A self-exciting generator often fails to build up when started but the cause generally can easily be located. If the machine fails to build up, the first thing to examine is the connection of the shunt field. It must of course be properly connected to the armature circuit. It may be that, even though the field circuit is properly connected to the armature, there is an open circuit somewhere. One of the connections between the various coils may be open. A bell-ringing magneto may be used to see if the field circuit is open, or a test may be made with any c-c. power line available; an incandescent lamp connected to a 110-volt line through the field circuit to be tested, will light if there is no open circuit but will not burn if the field is open somewhere. When this test is made, the field must be disconnected from the armature otherwise the armature forms a short circuit for the field.

Of course the generator cannot build up if the field circuit is open as its magnetic circuit cannot become excited.

17. There is always a rheostat in the shunt field of a generator and if this rheostat is turned to the "all in" position the generator will likely refuse to build up.

The current which flows through the shunt field circuit is equal to $E/R_{f+r}$ where

$E =$ the generated voltage

$R_{f+r} =$ the resistance of the field coils plus the field rheostat resistance.

Now suppose the magnetization curve of the machine is as given in Fig. 286, and $\tan \phi_1 =$ the resistance of the field circuit. (The same scale is supposedly used for both volts and amperes. If not, a proper change must be introduced in the value of $\tan \phi$.) With the resistance of the field circuit equal to $\tan \phi$, it is apparent that at no value of the field current (except at very low values) does the armature generate enough voltage to force through the

field circuit enough current to excite the field sufficiently to produce in the armature the voltage considered. Hence, with this value for the field circuit resistance, the generator could not build up.

But suppose that the field rheostat is all cut out so that resistance of the field circuit becomes equal to tan $\phi_2$. Now when the generator has a field current equal to $OD$ it generates a voltage $DE$. But to force the current $OD$ through the field circuit requires only the voltage $DB$.

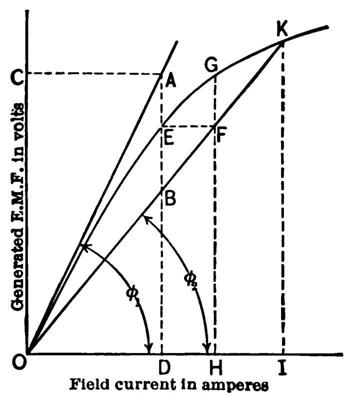


FIG. 286.—Diagram to Show Why a Generator Refuses to Build up if There is too Much Resistance in its Shunt Field Circuit.

Hence the voltage $DE$ forces through the field circuit a current $OH$, which in turn makes the armature generate the voltage $HG$, which again increases the field current. This process continues until the point $K$ is reached where the generated voltage is just sufficient to force through the field circuit the current at $OI$.

Therefore, in starting a shunt generator, it is necessary to properly reduce the resistance in the field rheostat.

**18. A dirty commutator produces the same effects as** field rheostat resistance. The high contact-resistance

of the brushes on the commutator (due to the dirty surface) acts just the same as a high resistance in the field rheostat. The commutator may be cleaned by holding a piece of oily rag on the revolving commutator; the oil will generally loosen the sticky, black coating which forms on a commutator surface. The commutator should always be cleaned after applying oil to its surface.

**19.** The brushes may have been disturbed and then set in the wrong position so that, even if the field were excited, there would be no voltage on the armature terminals. The brush should rest on that commutator bar to which is connected the coil which lies in the interpolar space; whether or not this is so may generally be ascertained by tracing the end connections of the coils.

**20.** In discussing the "building up" of a self-exciting generator we showed that some residual magnetism is necessary to start the process. If, due to some jarring, reversed current, or similar cause, the field frame has lost its residual magnetism, it is necessary to re-magnetize the field by supplying current to the field coils from some outside source. A few primary cells will generally be sufficient to give the requisite amount of residual magnetism. Before connecting the cells to the shunt field circuit the field must be disconnected from the armature, otherwise the low resistance armature forms a short circuit for the field and the current from the cells, instead of flowing through the field, practically all goes through the armature.

**21.** The residual magnetism may have reversed so that what small current is sent through the field circuit by the voltage due to residual magnetism tends to decrease, instead of increase, the field magnetism. In this case the residual magnetism must be reversed or else the connection of the field circuit to the armature may be reversed. This latter procedure is permissible only in the laboratory because it will cause the generator to build up with reversed polarity. If this were done on a railway generator, for

example, the station meters would all deflect backward and the polarity of trolley and ground would be reversed Such a condition would necessitate a complete change of the meter connections or of the connection of the generator to the bus-bar.

If it is necessary to reverse the residual magnetism, a few dry cells will generally suffice. The shunt field is disconnected from the armature, at one terminal, and the dry cells (perhaps half a dozen) are connected to the field circuit for a few moments. Then the cells may be disconnected, the field connected again to the armature, and the generator may start to build up alright. In case it does not, the operation should be repeated, connecting the cells to the field, however, with polarity opposite to that first used.

In carrying out this operation, it is, of course, necessary to disconnect the armature from the shunt field as the armature would otherwise form practically a short circuit (as it has such a low resistance) for the shunt field; the current from the dry cells would nearly all go through the armature, and so be useless for magnetizing the field.

**22.** If a generator is running at a speed very much lower than rated speed, it will very likely refuse to "build up." The speed should be increased until the rated value is reached.

**23.** When a motor fails to start, the first thing to determine is whether or not the supply line is alive. This is readily tested by a voltmeter or by an incandescent lamp on a 110- or 220-volt circuit. On a 500-volt circuit several incandescent lamps may be connected in series with each other and then connected across the line to test for voltage.

**24.** All motor circuits should be fused and it may, of course, be that the fuses are blown. This may be determined by an inspection of the indicator on an enclosed fuse or by testing the fuse in series with an incandescent lamp

across the line. If the fuse is blown, of course, the lamp will not burn.

**25.** Either the field or the armature circuit may be open. The field circuit may be tested by holding the starting rheostat lever on the first contact button and with the armature stationary, testing for magnetism on the pole shoes with a knife, keys, or similar article. If the field has no magnetism, it shows that the field circuit is open (provided the line is alive) and this open circuit must be located and removed.

The armature circuit may be open in the armature itself or in the starting box. The open circuit may be found with a bell-ringing magneto, by trying to ring through the different parts of the circuit.

**26.** If all of the resistance is "cut in" on the field rheostat, it may be that the torque the motor can develop with the weak field is not sufficient to start the load. The field rheostat should be turned to the "all out" position.

**27.** It may be in some cases, that the starting torque demanded of a motor is greater than the motor can exert. On factory loads, where a great deal of belting is used, this is especially likely to be true. In such a case some of the belting must be disconnected from the motor, by a releasing clutch or similar device, until the motor is up to its normal speed. If this is not possible, a larger motor must be installed.

**143. Location of Armature Faults.** The three faults which are most likely to occur in an armature circuit are due to *short circuits, open circuits, or grounds.* An armature winding consists of a series of similar coils, all joined in series and insulated from the armature core. If the winding becomes electrically connected to the core at any place, due to abrasion or the cutting of the insulation on the coils, the winding is said to be *grounded.* One ground in an armature winding does not interfere with the electrical operation of the machine, but the iron frame of the machine,

being electrically connected to the armature winding, may give a fatal shock to an operator coming in contact with it.

The frame of any electric machine should be well insulated from the winding and it is advisable to actually connect the framework of the machine to a ground connection, such as a waterpipe. Then the operator will not receive a shock upon coming in contact with the frame of the machine even though the winding should become grounded on the iron frame of the machine.

The location of a short-circuited coil, open-circuited coil or ground is easily carried out with the help of very simple apparatus.

*To Locate a Short-circuited or Open-circuited Coil.* Remove

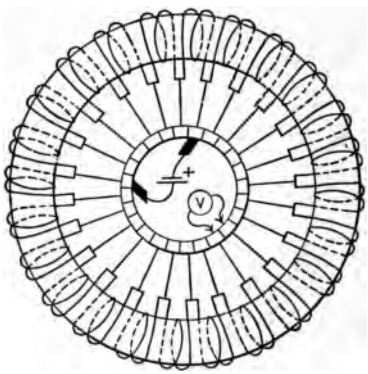


FIG. 287.—Connections for Locating a Short-circuited or Open-circuited Coil.

all the brushes from the commutator but one pair. Connect a dry cell to the pair of brushes, as in Fig. 287. Then with a low reading voltmeter (the full range of which is somewhat greater than the e.m.f. of the dry cell) read the $IR$ drop between every adjacent pair of commutator segments. If there are no short-circuited coils or open-

circuited coils the *IR* drops in the various coils will be the same. Of course, if there are more coils in one path of the armature winding than in the other the drop per coil will be different. *But all the coils in series with each other in one path should have the same drop.* If a short-circuited coil is present it will be indicated by a zero *IR* drop, or, at least, by an *IR* drop much smaller than that of the other coils. An open-circuited coil is indicated by a zero *IR* drop across all of the coils in the same armature path, except the open-circuited coil, and the full voltage of the cell across the coil which is open-circuited.

After all coils have been tested as far as possible the armature should be revolved slightly so that the coils connected to the commutator segments under the brushes may be tested.

As has been mentioned before a short- or open-circuited coil, on an armature which has been in service, can generally be located by the burned condition of those commutator bars to which it is connected.

*Test for a Grounded Winding.* A test to see whether or not the winding is grounded may be made by connecting one side of a 110-volt line, through a voltmeter, to the shaft of the armature and connecting the other side of the line to any bar of the commutator. If the meter gives an appreciable reading, it indicates a ground in the winding because, if the winding was perfectly insulated no current could flow through the voltmeter to make it indicate. Whether or not the winding is badly grounded is determined by the magnitude of the reading. If the meter gives a high reading, the winding is poorly insulated; a low reading signifies a well-insulated winding. A well-insulated armature should give, with the ordinary c-c. voltmeter, less than one volt when such a test is made. If the magnitude of the reading is the same as though the meter were connected directly to the 110-volt line, it indicates that there is a bad ground somewhere in the winding, a ground so

bad that no insulation at all exists between the armature circuit and the core.

*To Locate a Grounded Coil.* To locate the grounded coil of an armature all brushes are removed but one pair, as for the previous test. The dry cell is connected to the brushes as before, and one terminal of the voltmeter is connected to the shaft of the armature and the other is connected in turn to all of the commutator segments, as indicated in Fig. 288. If there is no ground, the readings will all be alike, while if a ground exists, the voltmeter will give continually varying readings, it being practically zero

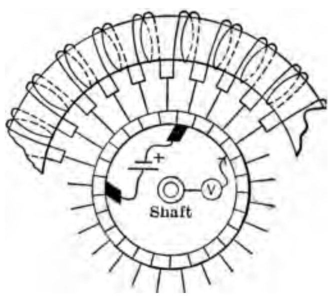


FIG. 288.—Connections for Locating a Grounded Coil.

on one of the segments. This segment is connected directly to the grounded coil.

*Real Ground and Phantom Ground.* Now it will be found that *each path indicates a grounded coil;* one of them is called a *phantom ground.* The two paths in the armature being in parallel, if there is a point in one path which has the same potential as the armature shaft (indicated by a zero reading of the voltmeter), there must be in the other path a corresponding point of zero potential which also will give a zero reading on the voltmeter.

The two segments giving zero reading are marked with chalk and then the armature is rotated a fraction of

a revolution and the test repeated. Two apparent grounds will again be detected, one in each path, but it will be noticed that one of the segments is the same as was detected before, while the other is now on a different segment than it was. That ground which persists on the same commutator bar is the only real ground; the one which shifts from one segment to another as the armature is revolved is a phantom ground only, as the winding is really not grounded in this place at all. As the armature is turned in several positions and tested each time, it will be noticed that the phantom ground moves on the structure in the opposite direction to that in which the armature has been moved while the real ground turns just as the armature is turned.

*Use of a Bell-buzzer for Making Tests.* Instead of using a voltmeter for these tests a telephone receiver may be employed if the dry cell is connected to the brushes through a bell-buzzer. This is a very convenient way of testing as a suitable low reading voltmeter is not always available.

*Repairing an Armature.* Repairing a faulty armature generally requires considerable skill and should not be attempted by the average operator. A repair man from the factory should be employed or, if the armature is a small one, it may be shipped back to the factory for repairs.

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